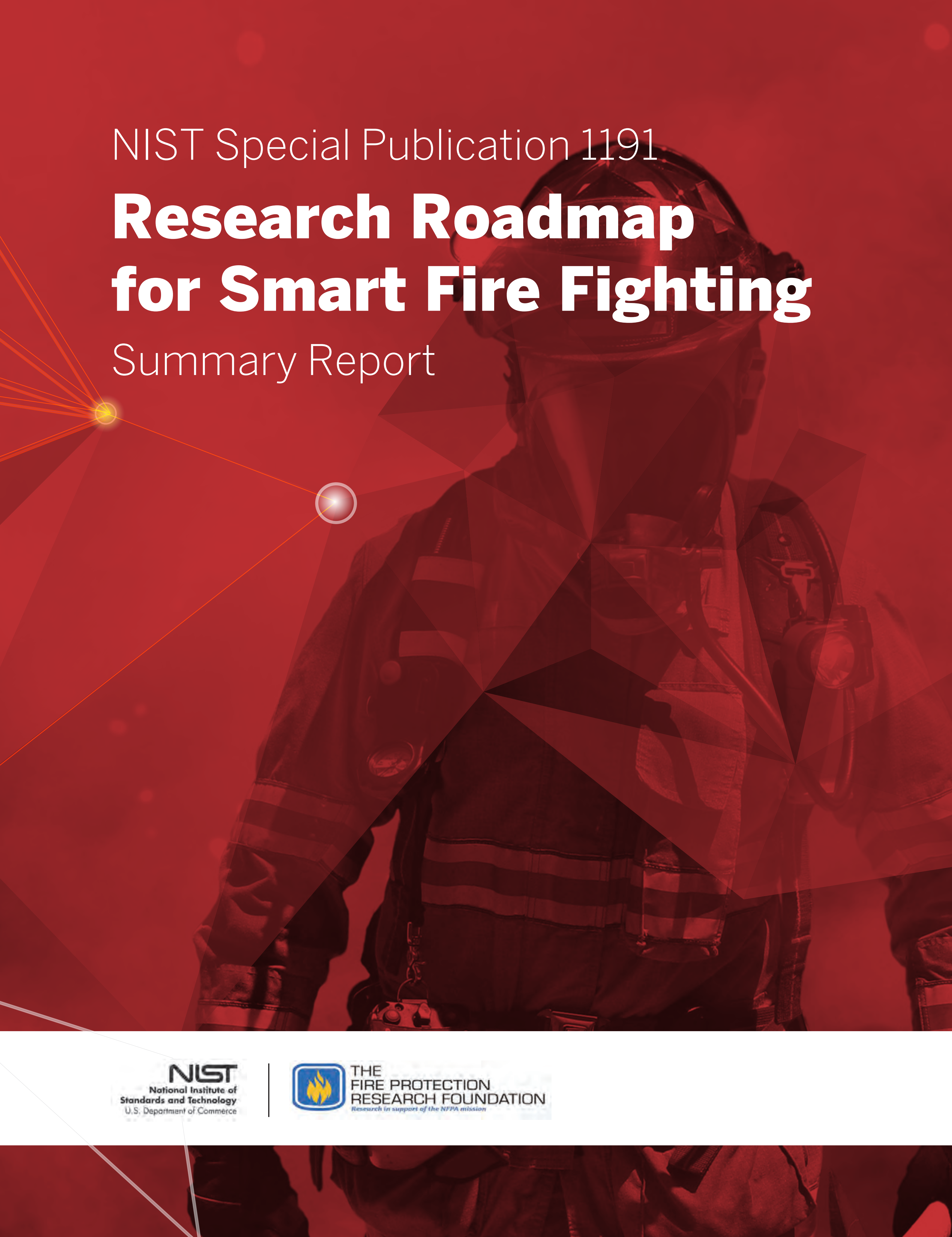

NIST Special Publication 1191

Research Roadmap for Smart Fire Fighting

Summary Report

National Institute of Standards and Technology
U.S. Department of Commerce

THE FIRE PROTECTION RESEARCH FOUNDATION
Research in support of the NFPA mission

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Research Roadmap for Smart Fire Fighting

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List of Acronyms

7FP	7th Framework Program
ACA	Affordable Care Act
ACGIH	American Conference of Governmental Industrial Hygienists
ACNS	advanced crash notification systems
AEDs	automatic external defibrillators
AFD	autonomous fire detector
AFFMP	Autonomous Fire Fighting Mobile Platform
AIAA	American Institute of Aeronautics and Astronautics
AMS	autonomous modular sensor
ANI-ALI	automatic-number-identification/ automatic-location-identification
ANSI	American National Standards Institute
AODV	Ad hoc On-Demand Distance Vector
APCO	Association of Public-Safety Communication Officials
APIs	application programmer interfaces
AR	augmented reality
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASVs	unmanned or autonomous surface vehicles
ATF	Bureau of Alcohol, Tobacco, Firearms and Explosives
AVL	automatic vehicle location
BAER	burn area emergency response
BATS	Bomb Arson Tracking System
BIM	building information modeling
BMS	building management systems
CAC	Command Access Card
CAD	computer-aided design
CAD	computer aided dispatch
CAN	conditions, actions, and needs
CAP	Common Alerting Protocol
CATT Lab	Center for Advanced Transportation Technology Laboratory
CBR	chemical, biological, or radiological
CCCT	Computing, Communications and Control Technologies
CCTV	closed-circuit television
CIF	Common Industry Format

CIRC	Critical Infrastructure and Resilience Center of Excellence
CMAS	Commercial Mobile Alert System
CNN	Cellular Neural Network
CO	carbon monoxide
COaP	Constrained Application Protocol
COE	Center of Excellence
COLT	cell on light truck
COTS	commercial off the shelf
COW	cell on wheels
CPS	cyber-physical systems
CRGs	community response grids
CSMA/CA	Carrier Sense Media Access/Collision Avoidance
d2d	device-to-device
DA	data assimilation
DARPA	Defense Advanced Research Projects Agency
DC HSEMA	District of Columbia Homeland Security and Emergency Management Agency
DHCP	Dynamic Host Configuration Protocol
DHS	Department of Homeland Security
DIY	do-it-yourself
DM	Device Management
DMA	differential mobility analyzers
DMs	decision makers
DNSs	Domain Name Servers
DOJ	Department of Justice
DOT	Department of Transportation
DPWS	Device Profile for Web Services
EAS	Emergency Alert System
ECG	electrocardiogram
EKG	electrocardiogram system
EMD	emergency medical dispatch
EMS	emergency medical service
EMT	emergency medical technical
EOST	end of service time
EOSTI	end-of-service time indicator
EPA	Environmental Protection Agency

ERC	Engineering Research Center
ERCIM	European Research Consortium for Informatics and Mathematics
ERESS	emergency rescue evacuation support system
ESE	electronic safety equipment
EU	European Union
FCC	Federal Communications Commission
FDNY	New York City Fire Department
FEMA	Federal Emergency Management Agency
FFO	Federal Funding Opportunity
FLASH	Fire Line Advanced Situational Awareness for Handhelds
FOA	Funding Opportunity Announcement
FPRF	Fire Protection Research Foundation
FTIR	Fourier transform infrared
GETS	Government Emergency Telecommunications Service
GIS	geographic information system
GLANSER	Geospatial Location Accountability and Navigation System for Emergency Responders
GLM	generalized linear models
GPS	Global Positioning System
hazmat	hazardous materials
HIPPA	Federal Health Insurance Portability and Privacy Act
HIS	Homeland Security Institute
HMD	head-mounted display
HST	Homeland Security
HUDs	Heads-up displays
HVAC	heating, ventilation, and air-conditioning
IAFC	International Association of Fire Chiefs
IC	incident commander
ID	caller identification
IDLHs	Immediately Dangerous To Life or Health Concentrations
IMETI	International Multi-Conference on Engineering and Technology Innovation
IoT	Internet of Things
I&P	Industry and Practitioner
IPAWS	Integrated Public Alert and Warning System
IPAWS-OPEN	IPAWS Open Platform for Emergency Networks
IR	infrared

ISCRAM	International Conference on Information Systems for Crisis Response and Management
ISM	industrial, scientific, and medical
ISORC	International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing
LAN	local area network
LEDs	light-emitting diodes
LLA	link-local addressing
LMRs	land mobile radios
LoS	line-of-sight
LTE	Long-Term Evolution
LWM2M DM	Lightweight M2M Device Management
MAC	media access
MAE1	mutual aid engine
MANETs	mobile ad hoc networks
MBAS	Mutual Box Alarm System
MBD	model-based design
MEMS	microelectromechanical system
MFRI	Maryland Fire and Rescue Institute
M2M	machine-to-machine
MOSFET	metal-oxide semiconductor field-effect transistors
MQTT	MQ Telemetry Transport
NAWAS	National Warning System
NDM	naturalistic decision making
NEMA	National Electrical Manufacturers Association
NEMSIS	National EMS Information System
NENA	National Emergency Number Association
NFC	near-field communications
NFIRS	National Fire Incident Reporting System
N-FORS	National Fire Operations Reporting System
NFPA	National Fire Protection Association
NG9-1-1	Next generation 9-1-1
NIMS	National Incident Management System
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development

NOAA	National Oceanic and Atmospheric Administration
NOMS	Network Operations and Management Symposium
NPSTC	National Public Safety Telecommunications Council
NSF	National Science Foundation
NTIA	National Telecommunications and Information Administration
O2	oxygen
OASIS	Organization of the Advancement of Structured Information Standards
OEM	original equipment manufacturer
OMA	Open Mobile Alliance
OPCs	optical particle counters
OTA	over-the-air
OUP	Office of University Programs
P25	Project 25
PACR	pre-arrival coverage rate
PAN	personal area network
PASS	personal alert safety system
PHASER	Physiological Health Assessment System for Emergency Responders
PM	particulate matter
p2p	peer-to-peer
PPE	personal protective equipment
PPV	positive-pressure ventilation
PSAPs	public safety answering points
PSWAC	Public Safety Wireless Advisory Committee
PUMA	Portable Unit for Metabolic Analysis
QCM	quartz crystal microbalances
RBIS	Risk-Based Inspection System
RDF	Resource Description Framework
RET	Research Experience for Teachers
RF	radio frequency
RFID	radio frequency identification
RITIS	Regional Integrated Transportation Information System
RIT/RIC	rapid intervention teams or crews
RMS	record management systems
ROC	receiving-operating characteristic
ROSS	Resource Ordering Status System

SA	situational awareness
SAC	Smart America Challenge
SAFER	Situational Awareness for Emergency Response
SAR	search and rescue
SAW	surface acoustic wave
SCADA	Supervisory Control and Data Acquisition
SCALE	Safe Community Alerting Network
SCBA	self-contained breathing apparatus
SCUBA	self-contained underwater breathing apparatus
SDRs	software-defined radios
SERS	Smart Emergency Response System
SFF	Smart Fire Fighting
SJC	Selectable Joystick Controlled
SMS	short message service
SNIFFR	Smart Network Infrastructure for Fire Resilience
SoC	system-on-chip
SOP	standard operating procedure
SQuaRE	Software product Quality Requirements and Evaluation
SSBT	Sensor, Surveillance, and Biometric Technologies
SSL	Secure Sockets Layer
SSRR	Safety, Security and Rescue Robotics
SVS	synthetic vision system
TCs	Technical Committees
TCP	Transmission Control Protocol
TEOM	tapered element oscillatory microbalances
TIC	thermal imaging camera
UAS	unmanned aerial systems
UAV	unmanned airborne/aerial vehicles
UDP	User Datagram Protocol
UGVs	unmanned ground vehicles
UL	Underwriters Laboratories, Inc.
UNB	Ultra-Narrowband
UPnP	Universal Plug-n-Play
URIs	Uniform Resource Identifiers
USBDC	U.S. Bomb Data Center

USFA	U.S. Fire Administration
USVs	unmanned or autonomous surface vehicles
UUVs	unmanned underwater/undersea vehicles
VANETs	Vehicular ad hoc networks
V2I	vehicle-to-infrastructure
VOI	value of information
V2P	vehicle-to-pedestrian
VR	virtual reality
V2V	vehicle-to-vehicle
WAN	wide area network
W3C	World Wide Web Consortium
WCDE	wildfire collaborative decision environment
WEA	Wireless Emergency Alerts
WLAN	Wireless local area network
WPAN	wireless personal area network
WPI	Worcester Polytechnic Institute
WPS	Wireless Priority Service
WRECS	Worcester Polytechnic Institute Robotics Engineering C Squad
WSNs	Wireless sensor networks
WUI	wildland-urban interface
XMPP	Extensible Messaging and Presence Protocol

Overall Abstract

In 2013, fire departments in the United States responded to more than 480,000 structure fires [1]. These fires resulted in approximately 2850 civilian fatalities, 14,000 injuries, and estimated property losses of $10 billion dollars. More than 30,000 fire fighters were injured on the fireground [2]. These losses can be significantly reduced by exploiting new opportunities in technology development, including cyber-physical systems through the fusion of emerging sensor and computing technologies with building control systems, fire-fighting equipment, and apparatus. Cyber-physical systems will revolutionize fire fighting through a range of approaches most notably represented by collecting the data globally, processing the information centrally, and distributing the results locally.

The overarching goal for this work is to develop a research roadmap that establishes the scientific and the technical bases to achieve what is being called Smart Fire Fighting. The vision for Smart Fire Fighting involves the following:

- Saving lives and minimizing injuries to building occupants and community members
- Improving fire fighter occupational health and safety
- Enhancing the overall operational efficiency of the fire service and the effectiveness of fire prevention and protection
- Minimizing property loss from fire
- Minimizing business interruption and loss of mission continuity due to fire

Smart Fire Fighting includes all areas of fire prevention and protection engineering and fire service emergency response, and it addresses all phases of resilience (i.e., pre-incident, during an incident, and post-incident). Smart Fire Fighting will transform traditional fire protection and fire fighting practices to ensure the flow of critical information where and when it is needed. Fire prevention is an essential element of Smart Fire Fighting. This will be achieved by enhancing the power of information through enhanced data gathering, processing, and targeted communications. An evolving range of databases and sensor networks will be tapped to create, store, exchange, analyze, and integrate information into critical knowledge for the purpose of Smart Fire Fighting. Engineering, developing, and deploying these systems will require new measurement tools and standards, among other technology developments. This roadmap identifies and addresses high-priority measurement science research challenges, technical barriers, and related research and development gaps that hinder widespread application of Smart Fire Fighting technologies and systems to enhance building and community fire protection.

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2. Karter, M. J., and J. L. Molis. 2014. *U.S. Fire Fighter Injuries 2013.* Quincy, MA: National Fire Protection Association.

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SECTION

1 INTRODUCTION

CHAPTER 1

Background and Vision

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fire service emergency responder

Abstract

Fire losses throughout the world remain too high and fire fighting too hazardous. Today, data from a variety of sources are collected independently and processed separately, but evolving new technologies are enabling the use of vast amounts of information. The use of this information continues to demonstrate great promise at enhancing the effectiveness and efficiency with the duties handled by fire fighters. Importantly this equates to improved safety and health for this high risk profession, via situational and incident awareness and other factors. Knowledge is power, and harvesting the data important to fire fighters is empowering the smart fire fighter of the future.

1.1 Introduction

In 2013, fire departments in the United States responded to more than 480,000 structure fires, which caused close to 2850 civilian fatalities, 14,000 injuries, and property losses of approximately 10 billion dollars [1]. More than 30,000 fire fighters were injured on the fireground [2]. Such losses can be significantly reduced by exploiting the abundance of new cyber information (both software and hardware) technologies being deployed in a number of other domains such as manufacturing, health care, and the power grid. The introduction and integration of new technologies into those areas have led to new types of systems called **cyber-physical systems (CPS),** which in turn have resulted in greatly improved performance, safety, prediction, and resilience.

A similar transformation can lead to analogous benefits for fire protection and fire fighting. The introduction of appropriate technologies and systems will facilitate the fusion and use of a wide array of real-time sensor data from the community, buildings, fire fighters, equipment, and fire apparatus during not only an emergency event but also the pre-events (e.g., code enforcement, prevention, training) and the post-events (e.g., overhaul, salvage, investigation). These data have the potential to enhance fire protection and situational awareness on the fireground and, together with information from cloud-based databases, will provide valuable input for computational models and decision tools. The result will be better predictions of the likely evolution of an incident, leading to better tactical decisions.

The use of technology in this manner, referred to here as **Smart Fire Fighting**, includes all areas of fire protection engineering and phases of fire service emergency response: pre-incident, during-incident, and post-incident. Smart Fire Fighting will transform traditional fire prevention and protection strategies and fire-fighting practices by ensuring the flow of critical information where and when it is needed. This flow will be achieved by increasing the power of information through enhanced data gathering, processing, and targeted communications. The engineering, development, and deployment of cyber-physical systems for fire fighting will require new measurement tools and standards, among other technology developments. A roadmap is necessary to identify and address high-priority measurement science research challenges, technical barriers, and related research and development gaps that hinder widespread application of Smart Fire Fighting technologies and systems. This chapter is an overview of the current state and future trends and clarifies the vision of Smart Fire Fighting. It also describes the scope and purpose of the roadmap, research challenges for cyber-physical systems, and next steps.

1.2 The Current State of Fire Fighting

1.2.1 "House Fire at 135 Maple Street; Truck 51, Engine 81, Ambulance 61 Head Out"

Upon receiving a 9-1-1 call, the emergency communication center issues an alert, dispatching equipment and personnel to the incident. Emergency responders receive the alert and immediately initiate transit to the fireground. Addressing the situation to the best of their ability, the fire fighters work to control the fire and ensure the safety of the building's occupants. According to common practice (i.e., SLICE-RS/DICERS, from the International Society of Fire Service Instructors and FDNY), fire fighters need to Size up the incident, Locate the fire, Identify the fire, Cool the fire from a safe distance, Extinguish the fire, Rescue, Salvage, ventilate, and overhaul efficiently, effectively, and safely [3]. DICERS adds the important Detect and Isolate functions at the front end of the size and locate steps and emphasizes the Rescue and Salvage missions following the Confine and Extinguish steps. An incident commander (IC) arrives on scene to manage the entire process, which can involve multiple responders and apparatus from various jurisdictions. The IC's ability to manage this process can be extremely challenging, particularly because these situations typically are highly information limited and rapidly changing. Regardless, it is the IC's responsibility to ensure an efficient, safe, and effective response.

Available information on the situation becomes apparent piecemeal — neither collected nor processed in a systematic fashion. Consequently, the progression of events associated with the incident can be protracted. Small teams of fire fighters analyze their immediate situation, based on locally collected data, and take action based solely on that analysis. Some teams can communicate their situation and their actions over radio to the IC, others cannot. The IC combines whatever information comes from the teams with past experiences to build a mental model of the entire fireground and then issues commands to the teams based on that model. The IC might command one team to initiate search and rescue operations and another team to ventilate the structure to clear smoke and hot gases from the building.

If the IC's mental model is incorrect or the commands are misunderstood or misinterpreted, the timing and implementation of key tasks could be seriously flawed. For example, the ventilation team could begin its task too early or in the wrong location, resulting in the search and rescue team being trapped. Bad things happen too often, and there are too many injuries, fatalities, and near misses for fire fighters and building occupants. Frequently, ICs do not learn of the success or failure of their individual commands or of the entire process until the teams and the occupants emerge from the structure.

Scenes like this one play out hundreds of times a day, every day, every year. While the fireground is rich with information, decision making on the fireground is data limited. The approach used thus far — of independent and incomplete data collection, constrained analysis, and action with limited coordination — hampers an IC's ability to optimize tactical decisions. If lucky and skillful, the fire fighters and emergency medical services personnel are successful despite the chaos. If the situation changes unexpectedly, if information is communicated incompletely or incorrectly, and if inappropriate decisions are made, lives and property often are lost.

1.2.2 Why Is It This Way?

There are more than 30,000 fire departments in the United States and almost as many operating procedures for fighting fires. Why is that? Because there are no national standards for such procedures! While standards exist for training, equipment, and other key focus areas, tactics and strategies typically are controlled by three major factors: (1) the experience and judgment of the IC; (2) limited data that are either visually observed or derived from the operating environment, such as a fire alarm panel or fire command center; and (3) jurisdictional standard operating procedures. At a fire incident, the variation in these factors can be tremendous. If the fire service is working without specific and reliable information regarding the fire location, history, and projected growth; the building geometry and its contents; the location of occupants and fire-fighting personnel; the fire suppression activities and their consequences; and the status of fire protection assets, then their response strategy will continue to rely on experiential judgment.

Transformation of the paradigm of tradition-based, experiential fire fighting calls for data-driven methods coupled with computational software that can inform tactical, deployment, and operational strategies. Such methods and software have yet to be developed, tested, and demonstrated in the field to be more effective. As a result, decision making on the fireground is information limited — there is a lack of complete, real-time data on the fire, the building's occupants, and the fire fighters themselves. Very few sensors exist that provide quantitative, real-time information on the changing conditions on the fireground, the changing location of fire fighters, and the location and status of the building's occupants. Today, that information is transmitted among responders using limited communication links, mostly radio, and there is a lack of data on the extent and condition of the fire itself, including thermal conditions, the risk of flashover, the distribution of smoke, and the existence of toxic gas species. This combination of factors motivates interest in new approaches to emergency response to improve both situational awareness and decision making.

The current state of fire fighting and fire protection remains far from optimal despite efforts to exploit advances in technology, equipment, training, and communications [4]. Fire losses in the United States remain too high, and fire fighting is much too hazardous. The National Fire Protection Association (NFPA) estimates that the total annual cost of fire in 2011, including human and economic losses, costs of the fire service, built-in fire protection, and costs associated with the insurance industry was about 330 billion dollars, or roughly 2 percent of the U.S. gross domestic product [5].

1.3 A Vision of Fire Protection and Fire Fighting in the Future

At the highest level, the overarching goal for Smart Fire Fighting is to remove unwanted fire and other harmful events as a limitation to life safety, technical innovation, and economic prosperity. The vision to improve fire protection and fire fighting is undertaken with the following motivations:

- To save lives and minimize injuries to building occupants and community members due to fire
- To improve fire fighter occupational health and safety
- To enhance the operational efficiency of the fire service and the effectiveness of fire protection
- To minimize property loss from fire
- To minimize business interruption and loss of mission continuity due to fire

1.3.1 Scope and Purpose of the Roadmap

In this report, the term "Smart Fire Fighting" refers to all areas of fire protection engineering and **fire service emergency response**. All phases of these endeavors (i.e., pre-incident, during-incident, and post-incident) are addressed. The idea of Smart Fire Fighting is to exploit fully the power of information to address the nation's fire problems through enhanced data gathering, data processing, and targeted communications. Smart Fire Fighting will transform traditional fire protection and fire-fighting practices to ensure the flow of critical information where and when it is needed.

An evolving range of databases and sensor networks will be tapped to create, store, exchange, analyze, and integrate information into critical knowledge for the purpose of Smart Fire Fighting. Engineering, developing, and deploying these systems will require new measurement tools and standards. Information will come from many sources: from the community, from building occupants, from the building itself, and from fire fighters. Data from the community could include information about traffic, weather, police, and hospitals. Information from the building could include annotated computer-aided design models or blueprints about the architecture, materials, and utilities, and details on fire-related building sensors and equipment. Occupants might be able to provide information about the number, age, and condition of people in the building and any relevant health issues. At the first indication of a fire incident, the IC could use information from these repositories to plan an initial strategy for suppression and rescue and alert the necessary community services. That strategy would include the number and types of equipment and personnel needed at the fireground and the tactics that should be executed when they arrive.

Once the equipment and personnel are on scene, a temporary wireless network could be set up, deploying a number of different sensor technologies to obtain a comprehensive and accurate assessment of the evolving situation on the fireground. The sensors and the network would continue to operate as needed throughout the entire event. This streaming, real-time information would be transmitted to the IC, who would develop an operational plan as appropriate and issue commands to personnel. Personnel would be equipped with a variety of sensors, providing real-time data about their own conditions, their locations, the growth and spread of the fire, and suppression/rescue operations. The sensor-related data would come in three possible forms: text, audio, and video. The IC would use computational tools to integrate this information and update the operational plan as needed.

To update the operational plan, the IC would create and run a series of computational models of fire growth, smoke generation, structural integrity, evacuation, suppression, ventilation, environmental conditions, air and water supply, tenability, and resource allocation. Each of these models would access repository and sensor information as needed; integrate, process, and analyze that information; and return predictions or results of other models, which then would provide inputs for the IC to use in decision making. As additional real-time information is collected, it would automatically update the models, outputs, and predictions.

The outputs and predictions from those models could be used in multiple ways. In some cases, such as fire growth, the outputs and predictions could be sent directly to personnel at the fireground or to other community services. If the model were to predict that the fire might spread into a portion of a building where toxic compounds are known to be stored, the model could be integrated with a smoke-generation model and a weather model to predict the likely impact on the surrounding community. That information then would be sent directly to law enforcement agencies and local hospitals to enable planning for a potential evacuation and treatment of victims. In most cases, model outputs and predictions would drive real-time 3D visualization of the fireground, equipment, and personnel. The IC would use the display to monitor the evolution of the fire incident and to analyze the potential impact of decisions and actions before issuing any commands to personnel. The visualization then would be recorded for future analysis, lessons learned, and training.

1.3.2 The Vision for Smart Fire Fighting

The Smart Fire Fighting vision includes the collection and integration of information from a wide range of databases and sensor networks. It also includes computational tools to analyze that information to make predictions of fire growth, building performance, occupant evacuation, and fire suppression. The realization of this vision would allow fire departments to coordinate better with other community services and fire fighters to execute fireground operations more effectively.

The vision of Smart Fire Fighting can be realized by harnessing the power of emerging information, communication, sensor, and simulation technologies to enable markedly better situational awareness, predictive models, and decision making. Many of the most exciting uses of those technologies are in the area of cyber-physical systems [6, 7]. See an example of this process illustrated in Figure 1.1.

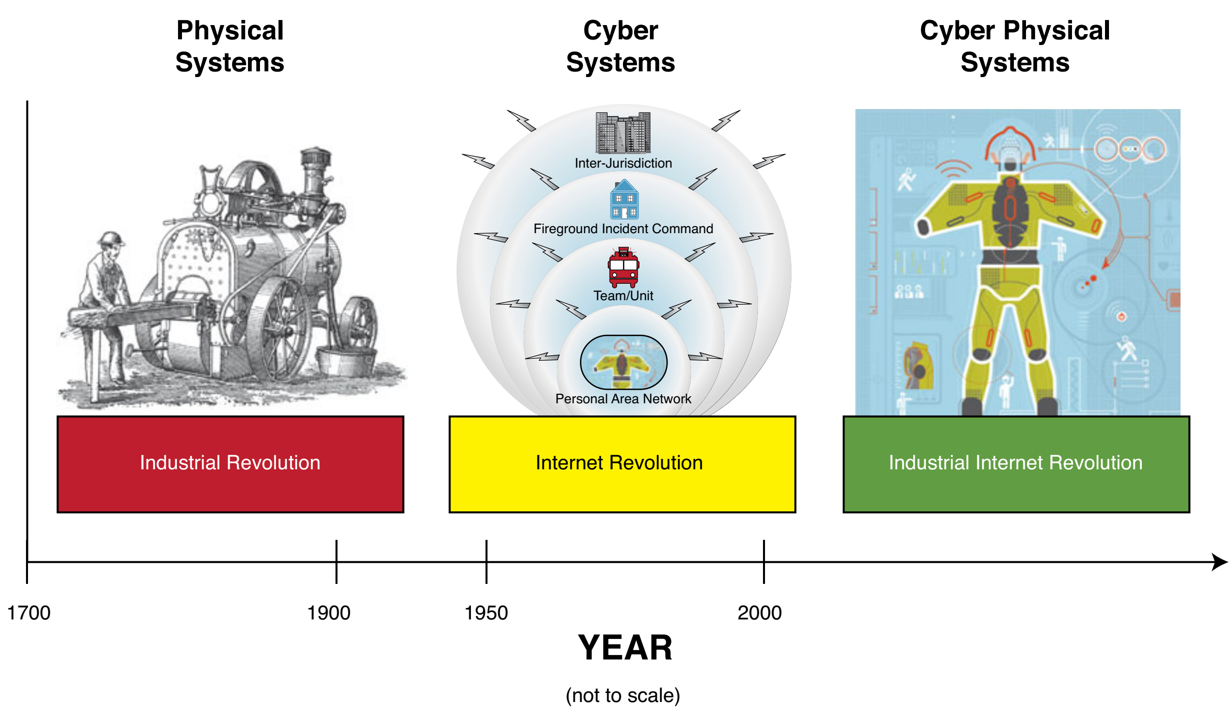
1.4 Cyber-Physical Systems (CPS)

From a historical perspective (see Figure 1.2), a major technology revolution is underway. The Industrial Revolution during the 18th century spearheaded major advances in physical equipment, technologies, and systems. Then, during the second half of the 20th century, the Internet Revolution led to fundamental advances in cyber hardware, software, and systems. The most recent development, the Industrial Internet Revolution, is leading to innovative advances in cyber and physical equipment, technologies, and systems. The Industrial Internet Revolution is leading to the Internet of Things (IoT), "big data," analytics, machine-to-machine communication, and a variety of sensors to acquire data, as well as new software to analyze those data. Used together, the equipment and technologies form an infrastructure for the establishment of CPS. CPS are being deployed in many sectors of society. The names are familiar and include the Smart Grid, Smart Homes, Smart Cities, Smart Buildings, Smart Healthcare, Smart Manufacturing, Smart Warfare, Smart Transportation, and Smart Infrastructure. CPS is transforming the way people interact with engineered systems, just as the Internet transformed the way people interact with information.

Because of their potential benefits to society, CPS are now, according to The President's Council of Advisors on Science and Technology, a national priority for federal R&D and are considered a potential economic engine [8]. Two major government agencies are promoting CPS: the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST). NSF is funding fundamental research in CPS through its Directorate for Computer and Information

Figure 1.1 Example of the Smart Fire Fighting process.

Figure 1.2 Historical perspective on technology development. (Source, far left: Shutterstock, Kuznetsov Alexey)



Science and Engineering. NIST is working on the measurements and standards associated with CPS through its internal research programs and the Smart America Challenge (SAC). SAC is promoting interconnection of CPS test beds and interoperability through shared data and associated data analytics.

1.4.1 The Evolution from Fire Fighting to Smart Fire Fighting

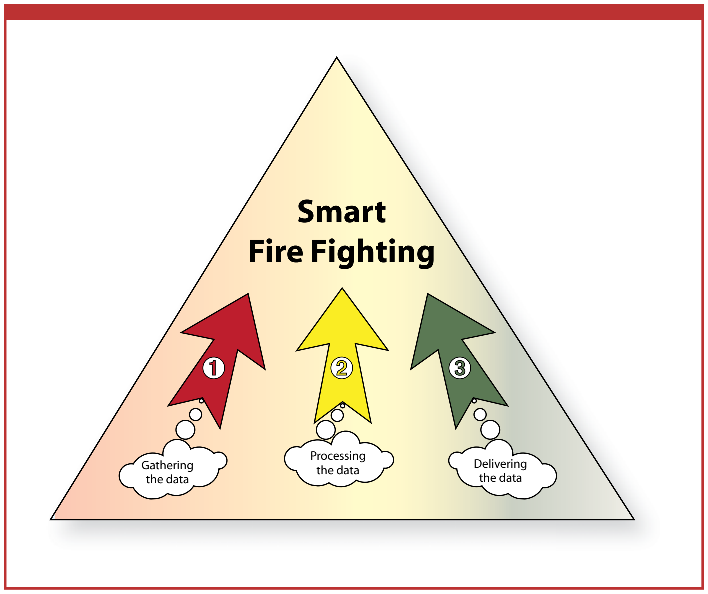
CPS combine the cyber world and the physical worlds with technologies that can respond with their surroundings in real time. The miniaturization of sensors and the power of computers coupled with wireless communication technologies have given rise to a range of commercial products that are being used in many application areas. These technology developments provide a sense of the types of previously unimaginable opportunities that are becoming available to improve the safety and effectiveness of fire fighting and fire protection. They enable the creation of fire-related products that talk to each other, and equipment and controls are integrated into meaningful subsystems involving fire fighter vehicles, building systems, fire fighter equipment and personal protective equipment (PPE), and community resources. Connecting the subsystems into an "enterprise system of systems" (or federated systems) is the ultimate goal, providing comprehensive access to available information.

When integrated, these technologies will facilitate the development of what we are calling Smart Fire Fighting, that is, a CPS for fire fighting and fire protection. The following enabling technologies are emerging or are already available:

- Autonomous vehicles and collision avoidance, addressing the 10 percent of fire fatalities associated with vehicle fires
- Mobile robots such as those in the most recent DARPA (Defense Advanced Research Projects Agency) Robotics Challenge, which in 2014, for the first time, focused on fire-fighting activities, including identifying a standpipe, transporting a bulky nonrigid fire hose, attaching the hose to the standpipe, and opening the spigot
- Smart clothing: shirts that measure heart rate, breathing rate, skin surface temperature, and triaxial accelerometry; boots that measure speed, distance, steps, and stride rates, with data wirelessly sent to a smartphone for analysis; and socks infused with textile sensors and paired with an electronic anklet that tracks steps, speed, altitude, and distance and that can detect jumping
- Augmented reality glasses that display enriched information over and above visible operations
- Mobile computing with millions of smartphone applications
- Global Positioning System (GPS) and enhanced mapping capabilities
- Big data, representing a new frontier in fire protection and emergency response, including data from real-time distributed sensors and databases distributed over the cloud
- The rise of multimedia, social media, and the Internet of Things, leading to the exponential growth of information with a large fraction of the population linked by cell phones
- BACnet®, the ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) data communication protocol for building automation and control networks, which will encourage technology integration, thereby increasing effectiveness and efficiency of individual equipment items such as building sensors [8]
- Smart Home fire alarm systems, which provide enhanced control over key building functions, including safety, security, entertainment, energy, and ambient environment
- FirstNet, the nationwide, interoperable, broadband network that will provide police, fire fighters, and emergency medical service professionals the ability to transmit and receive voice communications in seven ways, including push-to-talk functionality, group-call (one-to-many) capability, direct-mode (i.e., peer-to-peer or talk-around), full-duplex voice (like a traditional phone call), and with caller identification (ID)

Fire fighters operate in an ever increasing sensor-rich environment that is creating vast amounts of potentially useful data. The Smart Fire Fighting and smart fire protection of tomorrow are envisioned as using these technologies with a wide range of sensors and software tools to fully capture and exploit select data to perform work tasks in a highly effective and efficient manner. Behind the advances of the new sensors and tools are profound questions of how to best enable effective use of the deluge of valuable information. To address this problem, a new Smart Fire Fighting framework is needed.

Figure 1.3 Key concepts of the Smart Fire Fighting framework.



1.4.2 Smart Fire Fighting Framework

Smart Fire Fighting provides a framework to (1) collect and combine large quantities of information from a range of sources; (2) process, analyze, and predict using that information; and (3) disseminate the results and provide targeted decisions, based on those predictions, to communities, fire departments, ICs, and fire fighters, as appropriate. Figure 1.3 illustrates this concept in its simplest form.

This framework will need to address many measurement science and standards challenges, technical and implementation barriers, and environmental hazards on the fireground. The solutions will facilitate a paradigm shift from tradition-based fire protection and fire fighting to what is referred to here as *smart* fire protection and fire fighting. That shift will involve many changes and will transform fire protection and fire fighting from the current state of information-limited decision making to a sensor-rich environment with ubiquitous data collection, analysis, and communication, ultimately leading to data-driven and physics-based decision making (see Table 1.1). This shift will likely occur as CPS is developed and tested for various applications and employed for fire protection and fire fighting.

Table 1.1 Transformation from tradition-based fire fighting to Smart Fire Fighting.

Current State	Future State
Tradition-based tactics	Data-driven science-based tactics
Local information	Global information
Data-poor decision making	Information-rich decision making
Lack of awareness	Situational awareness
Untapped or unavailable data	Comprehensive data collection, analysis, and communication
Isolated equipment and building elements	Interconnected equipment and building monitoring, data, and control systems
Human operations	Human controlled, collaborative, and automated operations with inanimate objects (buildings, machines, etc.)

1.4.3 Gathering Information

Acquiring actionable information is critical for effective fire-fighting operations. The value of the information depends on its accuracy, completeness, and accessibility. While each information repository might have its own semantics, structure, and format, there need to be common protocols for information exchange if the data are to be shared and fully exploited. The value of information from a particular repository or source will depend on the scenario. At least four major types of information sources support Smart Fire Fighting: community-based information, building occupant information, building information, and information related to fire fighters and their tools (apparatus, equipment, PPE, etc.).

Communities manage several data repositories that house up-to-date information about traffic, weather, police, hospitals, and structures. Building repositories, for example, will have information — annotated computer-aided design models or blueprints — about the architecture, materials, utilities, and fire-related sensors and equipment. The occupants often can provide information about the number, age, condition, and health problems of people trapped in the building. At the first indication of a fire incident, the IC could use information from those repositories to plan an initial strategy for suppression and rescue and alert the necessary community services. That strategy would include the number and types of equipment and personnel needed at the fireground and the tactics that should be executed once they arrive.

Table 1.2 lists some of the existing and emerging sources of information that would be useful for Smart Fire Fighting. Today, data from these sources are independently collected and separately processed. Fire-fighting electronic equipment, such as self-contained breathing apparatus (SCBA), thermal imagers, and radios, do not communicate with each other; nor does fire fighting equipment communicate with building sensors, the fire apparatus, or community sources except in deliberate and essentially human-initiated serial activities. In effect, a vast amount of fireground data is untapped. To fully optimize the safety and effectiveness of fire fighting and fire protection, this situation needs to change and the systems need to become interoperable. As the trend for development of new electronic technologies continues, more and more data will become available for fire fighting and fire protection — information on fire fighter and building occupant location, fire fighter physiology, the state of a building, and fire conditions.

1.4.4 Processing and Targeting Information

Although the importance of information gathering in emergency response is apparent, the task of compiling, processing, and integrating the information into actionable knowledge is difficult. Examples of such information include fire loss records, fire inspection records, fire-fighting resource information, building information modeling, and building supporting infrastructure. Much of this information is stored in community resource databases and repositories.

At the first indication of a fire incident, the IC would use information from those repositories to plan an initial strategy for suppression and rescue and to alert the necessary community services. That strategy would include the number and types of equipment and personnel to send to the fireground and tactics they should execute once they arrive.

Others with important fire-fighting roles would also benefit from forecasts of the evolving incident. Examples of the types of processed information that could be useful in Smart Fire Fighting are listed in Table 1.3. To be meaningful, dynamic information needs updating as an incident evolves. Using real-time information to project the current and projected likely future states of the incident would allow identification of potential problems and provide a powerful tool to aid in decision making. The IC would use the display to monitor the evolution of the fire incident and to analyze potential effects of decisions and actions before issuing commands to the personnel.

1.4.5 Example Application Areas

The effort to develop the research roadmap for Smart Fire Fighting is based on the vision of enabling CPS to support and enhance fire protection and fire service activities. Table 1.4 describes emergency/safety scenarios typically encountered by emergency responders. These tangible case study scenarios are offered as examples for application of CPS to enable the Smart Fire Fighting of the future. The scenarios are based on actual events with similar characteristics. Their purpose is to stimulate consideration of possible data and information and to clarify both near-term and long-term deliverables.

Table 1.2 Example of existing and emerging fire-related information sources.

Source	Information Type
Fire Fighter	• Radio • PASS alarm • Thermal imaging cameras • SCBA cylinder pressure • Physiological monitoring • Fire hose water flow • Fire fighter location
Building	• Floor plans, firewall ratings, locations of standpipes, building entrances, interior stairwells, elevators, hazardous materials • Annunciator panel • Carbon monoxide alarm • Fire alarm • Activity/motion sensors • Fire sprinklers • Building information models • Surveillance cameras • Local temperatures • Occupant location
Fire Apparatus	• GPS routing, maps • Building pre-plans • Nearest hospital • Nearest hydrant • Apparatus water pressure • Accountability systems • Apparatus resource use
Community	• Community and regional resources • Computer aided dispatch • Detailed building plans (e.g., stairs, exits, utilities, standpipes, construction) • Weather information • Traffic information • Ambulance information • Hospital status/information • Community utilities (water pressure, power) • Fire loss records; fire inspection records

Table 1.3 Fire service dynamic information and knowledge needs.

Fire Service Role	Information Needed During an Emergency Event
Incident Commander (IC)	• Real-time forecast of fire location(s), size, and environmental conditions (tenability) • Crew and victim locations • Existing ventilation • Building status/forecast of time to significant failure in structural and situational tenability • Self-reporting by occupants of status (evacuated, still in the building) • Suggested situational tactics • Risk factors based on incident (locations of fire, fire fighters, occupants and conditions) • On-scene personnel, equipment, and resource assignments and locations • Health status of crew, victims, occupants • Available/en-route community resources (other departments, ambulance/hospital, police) • Hazard/injury forecasting from building and fire information based on risk associated with conditions such as gas species, thermal conditions, building collapse • Current and projected weather • City utility status and building utility control • Status of community-based emergency responders not on the scene (other fire departments, police, ambulance, etc.) • Hospital status (occupancy, resources, etc.)
Safety Officer	• Real-time forecast of fire location(s), size, and environmental conditions (tenability) • Injury forecast for crew members: risks based on physiological data and rate of change • Injury forecast from building and fire information: risk based on conditions such as gas species, thermal conditions, building collapse
Search and Rescue Team	• Real-time forecast of fire location(s), size, and environmental conditions (tenability) • Crew and victim locations • Prioritized search location list • Backdraft forecast • Projected nearest and alternate exit
Suppression Team	• Real-time forecast of fire location(s), size, and environmental conditions (tenability) • Crew and victim locations • Water pressure, flowrate, line length, line errors • Change in fire over time based on cleared area • Predictions of likely extensions from modeling • Suggested strategy for optimal output • Projected exit path
Ventilation Team	• Real-time forecast of fire location(s), size, environmental conditions (tenability) • Crew and victim locations • Existing ventilation • Expected ventilation results • Suggested location and type of ventilation • Projected exit paths for crew inside building • Structural tenability (especially roof)

In general, the scenarios in Table 1.4 are low-probability high-severity events. Their express intent is to maximize consideration of possible extreme events that fully test the available emergency responder resources. Fortunately, these events do not occur often for any particular fire service professional, but when they do, the proper execution of job tasks can literally make the difference between life and death. The knowledge delivered by CPS — and which enables Smart Fire Fighting — provides significant potential for enhanced fire fighting. That, in turn, equates with improving the health and safety of not only fire fighters but also the populations they protect.

Table 1.4 Case Study Smart Fire Fighting scenarios.

Type of Emergency/ Safety Scenarios	Events That Scenarios Were Based On	
	Historical Case Study Event	**Damage and Fatalities**
WUI (with evacuation of retirement community)	Waldo Canyon Fire, June 2012 in CO	2 civilian fatalities and 346 buildings destroyed
	Yarnell Hill Fire, June 2013 in AZ	19 FF LODDs and 129 buildings destroyed
Residential Structure Fire (wind-driven fire)	Based on Marsh Overlook Drive structure fire, April 2007 in Prince William County, VA	1 FF LODD
	Houston residential fire, April 2009 in Houston, TX	2 FF LODDs
	House fire, February 1995 in Pittsburgh, PA	3 FF LODDs
High-Rise Apartment Fire (wind-driven fire)	Based on Vandelia Avenue 10-story apartment fire, December 1998 in New York City	3 FF LODDs
Vehicle Crash (ICEV and EV with entrapment)	Based on NFPA statistics of U.S.: 17 vehicle fires per hour and 287,000 vehicle fires per year	
Train Derailment (with fire and toxic hazmat)	Based on Lac-Mégantic train derailment, June 2012 in Quebec	47 civilian fatalities and 30 buildings destroyed
High-Challenge Warehouse	Based on food product warehouse, December 2007 in Hemingway, SC	2-day fire and warehouse destroyed
Night Club Code Compliance	Based on Happyland Social Club fire, March 1990 in New York City	87 civilian fatalities
	Station Nightclub fire, February 2003 in West Warwick, RI	100 civilian fatalities
Tornado	Based on tornado, May 2011 in Joplin, MO	158 civilian fatalities and ~$2.8 billion loss
	tornado, May 2013 in Moore, OK (25 civilian fatalities and ~$2.0 billion loss)	
Terrorist Bombing (large-scale EMS event)	Based on Boston Marathon bombing, April 2013 in Boston, MA	3 civilian fatalities, 260+ injuries
Elevator Rescue (metro city power failure)	Based on substation fire causing widespread city center power failure, 2012 in Boston, MA	Hundreds of elevator rescue calls

Key to abbreviations: EV, electric vehicle; FF LODD, fire fighter line-of-duty death; ICEV, internal combustion engine vehicle; WUI, wildland-urban interface

1.5 Technical Challenges

The idea of Smart Fire Fighting is based on creating, storing, exchanging, analyzing, and integrating information from a wide range of databases and sensor networks. There are challenges associated with each of these areas. Among the key challenges is the ability to reliably design complex systems at an appropriate scale, which involves innovative design strategies, new control theory, systems integration, intelligent sensing and control, as well as automation. Another key challenge is the ability to develop usable performance metrics for experimentation, evaluation, and validation. These performance metrics are essential to enable the design, control, and efficient operation of advanced CPS. Another challenge is to enable interoperability among different CPS. This is essential to allow cities to connect their air quality, transportation management, emergency response, and other systems for safer and more resilient communities. The key to achieving interoperability is the development of consensus standards and protocols for interfaces within and between those complex systems.

1.5.1 Data Needs

Organizing the data needed for Smart Fire Fighting is a huge undertaking. Preparation for effectively managing a fire, whether in the urban, the wildland-urban interface (WUI), or the wildland environment, begins long before the actual incident. Effective management of fire events requires access to and processing of information collected prior to and after an event. Fire-service, data-user applications require information from inspectors and enforcers, pre-planning activities, training and education, and fire investigations. When preparing for and traveling to and from fire incidents, first responders must make many decisions quickly. That requires detailed and up-to-date information about the incident, including location, threats to resources and people, the emergency resources available, and the surrounding environmental conditions. Systems that provide this information can assist responders in determining the best of available actions to protect human life and to reduce threat and damage to resources. The required information can be obtained only from data collected prior to the event or after other previous, similar events. Similarly, accurate assessment of the effectiveness of equipment, tactics, and resources is best evaluated when complete information about incident characteristics, resource capabilities, and location characteristics are observed, recorded, and archived.

Data come in two forms, static and dynamic. Static data usually are stored in a number of different repositories, including fire loss records, fire-fighting resources, building information modeling, and building supporting infrastructure. The trend is to house those repositories in the cloud. While the cloud has several well-known benefits, it also presents several technical challenges, most notably cyber security [10].

Dynamic data come from sensors and radio communications. Those data are needed for real-time data analytics software applications to assess situational awareness. The results of the analyses are needed to assess risk (e.g., NFPA 1500, *Standard on Fire Department Occupational Safety and Health Program* [11]) and improve decision-making by fire fighters and by ICs. New computational software tools and virtual reality gaming engines are being developed to support both the risks and the decisions. Adequate metrics and testing tools have yet to be developed to determine the effectiveness of these new capabilities.

1.5.2 Sensors

The complex process of information gathering begins with sensors, which are becoming cheaper and more powerful. Sensors convert the characteristics of the physical environment involved in a fire emergency into raw data, thereby initiating the process of transforming what is perceived into actionable information. Today, the most common — and in some ways, most important —electronic sensor technologies associated with fire safety in residential buildings are smoke detectors [12].

The trend of new electronic technologies can provide an ever increasing, sensor-rich environment from which vast amounts of potentially useful data can be derived. Two areas where this trend is expected to continue are buildings and fire fighters. Buildings will see an increase in sensors that will track both environmental conditions and occupants' status. Fire fighters will be equipped with sensors that track the fire fighters' location, monitor their health, and sense their environment.

The key to widespread use and acceptance of these new sensors is standardization. Leveraging emerging sensor technologies and installed systems in buildings provides opportunities for Smart Fire Fighting. Continuing advances provide the possibility of integrating sensors into fire fighters' personal PPE, as well as equipment and apparatus (land vehicles, watercraft, aircraft, satellite, and robotic systems). The data from these sensors, which are often time critical [13], provide the capability to detect and characterize exposure hazards and to monitor the fire fighters' physiological status and location.

The combination of these sensory inputs allows both individual personnel and ICs to assess environmental conditions in real time and to take effective actions to minimize the associated risks. The ability to provide integrated sensors is interdependent on other features such as data logging and communication systems. Further, in order to integrate sensors, standards must be developed to support the necessary hardware and software interoperability.

These sensors will generate a wealth of new data. The availability of the data and the ability to analyze the data open new possibilities for the fire service. These possibilities will affect all their job duties, including those in the pre-fire, trans-fire and post-fire stages. NIST, NFPA, and many other organizations in the fire protection community are working to develop a roadmap to clarify the research needed to realize those possibilities. The roadmap includes the most effective ways to collect the immense quantity of available data, new computational tools to analyze the data, algorithms to convert that analysis into significant knowledge, heuristics to combine the knowledge with experience to enable better decision making, and wireless communication networks to transfer the information to those who need it on the fireground and elsewhere.

1.5.3 Architectures

A CPS architecture defines a system's components and their functions and interactions across temporal and spatial levels. There currently is no universal CPS reference architecture that enables collaboration and sharing of ideas and solutions within and across sectors and domains [14]. To make progress, Smart Fire Fighting systems and technologies require an integrated architectural design. Many CPS deployments are sector specific and fragmented and have not demonstrated their true potential of broad impact. The CPS research community is in the process of developing a framework to identify universal and cross-cutting elements of CPS architectures. In developing a CPS architecture for fire fighting, there is a need to be mindful of the architectures being developed for other CPS. This will help identify both common problems and common solutions.

1.5.4 Integration

Integrating sensor data with software analytics tools within and across architectural levels will require (1) standardized networking protocols to cover the wireless communications and (2) standardized syntax and semantics to cover the conceptual content. A number of wireless standards exist already, but there are issues regarding their effectiveness on the fireground. In other domains, ontologies and database standards have been successfully used to capture concepts in a way that provides the basis for modeling, programming, control, and communications. Often those concepts come from engineering, information technology, physics, and materials science. In fire fighting, concepts come from a number of other disciplines. To date, the use of ontologies in those disciplines has been virtually nonexistent. Such ontologies must be developed and tested before advanced diagnostics and prognostics can be used on the fireground. Expert understanding of fire protection engineering, fire science, and fire service will be needed to address realistic, challenging, and typical problems.

1.5.5 Standards

Standards are critical for the efficient development of Smart Fire Fighting. There has been some activity within traditional standards-development organizations to address the broad topic of CPS, although work on application-oriented subjects like Smart Fire Fighting has been relatively limited. Standardization will come in two forms: performance and protocols. Performance standards govern how sensors should function and the data they should provide. Protocols govern the integration of sensors with other physical or electronic equipment and related software applications. There will be many measurement issues associated with these standards, and it is important that the standards and measurements be developed and tested to ensure that the sensors work properly.

One arena in which the specific topic of Smart Fire Fighting is being addressed is the NFPA family of codes and standards. The NFPA Technical Committee on Data Exchange of the Fire Service is responsible for two proposed relevant documents: NFPA 950, *Standard for Data Development and Exchange for the Fire Service*, and NFPA 951, *Guide to Building and Utilizing Digital Information*. NFPA 950 is a new standard that describes the digital information structure and associated requirements and workflows common to fire and emergency services delivery, along with its management for emergency response and administrative use [15]. The standard provides a standardized framework for the development, management, and sharing of data for all-hazards response agencies and organizations. NFPA 951 will provide guidance on the development and integration of information and communications systems to facilitate information sharing for emergency response and national preparedness [16].

Another standard of direct interest to Smart Fire Fighting is ISO 37120, *Sustainable Development of Communities — Indicators for City Services and Quality of Life* [17]. The indicators are used to track and monitor a city's progress on city service performance and quality of life and to assist jurisdictions in setting targets and monitoring achievements. Fire fighting and emergency response are just two of a wide range of topics that ISO 37120 addresses.

Within the IEEE family of standards, there has been a focus on smart grid and some cross-cutting areas but not on Smart Fire Fighting. As interest in CPS evolves, integrated and coordinated standards efforts on CPS can be expected.

The National Electrical Manufacturers Association (NEMA) standard SB 30, *Fire Service Annunciator and Interface*, provides similarity across manufacturers' platforms to enable easy operation without the need for specialized training on each individual system. NEMA SB 30 was included in the 2013 edition of *NFPA 72®*, *National Fire Alarm and Signaling Code*, but since then has been rescinded, suggesting that work on standards development needs continuous maintenance and follow-up.

Connecting buildings to public safety networks will require careful consideration as the complexity of the issues involved in connecting a number of different networks using different protocols becomes more and more apparent [18, 19].

A large number of standards associated with Smart Fire Fighting remain to be resolved [20], including the following cross-cutting issues that affect all CPS:

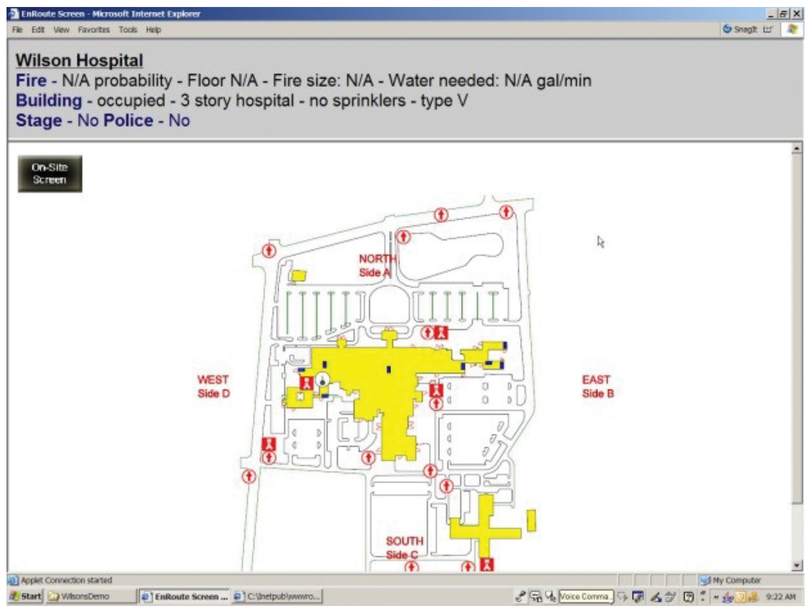
- Secure standard methods of transmitting a standard set of data in a standardized format
- Standardized information for first responders and standard building data models
- Ownership and maintenance of and data schemas and queries for databases
- Choice of standard communication protocols and user interfaces
- Establishment of criteria to automatically route 9-1-1 calls based on message content
- Implementation of appropriate authorization, authentication, and security protocols
- Development of multi-hazard scenarios for system design and compliance
- Interoperability standards for both software and hardware
- Standards for accessing and using cloud-based services
- Plug-and-play architectures that facilitate integration of cyber and physical components

1.5.6 Early Demonstrations of Smart Fire Fighting

An early demonstration of Smart Fire Fighting was conducted in 2005 by researchers at NIST and the Wilson, North Carolina, Fire Department in that city [21, 22]. The goal of the demonstration was to relay information to first responders on their way to a simulated incident, thereby improving decision making. Some of that information came from three sensors in the target building: smoke sensors, heat sensors, and CO detectors. The data from those sensors was used to by a zone fire model to infer probable future conditions. Other information, transmitted to first responders via a laptop computer en route (see Figure 1.4), included the following:

- Locations of fire hydrants, building entrances, interior stairwells, elevators, and hazardous materials
- Building construction and occupancy
- Real-time simulated fire size and location
- Locations or absence of sprinklers
- Locations of interior standpipes, fire wall ratings, and location of fire fighting and emergency medical services equipment
- Floor plans with fire hazards deduced from sensor signals using a zone fire model with indication of flashover, toxic/thermal hazard, significant smoke, or fire hazard

Figure 1.4 Screen-shot of en-route information displayed by emergency responder's laptop of the Wilson Hospital floor plan from [23]. Yellow indicates real-time toxic/thermal hazard areas based on a zone fire model calculation using simulated fire alarm data. (Source: Davis, W. D., "Intelligent Building Response," *Fire Protection Engineering*, No. 33, 26 Winter 2007.)



In 2009, an analogous system was implemented in the city of Frisco, Texas, 25 miles north of Dallas. Frisco invested significant resources to develop the SAFER project (Situational Awareness for Emergency Response). SAFER is an information-based system for first responders and community resources such as the Frisco emergency operations center, police dispatch, and a mobile command center. (See http://video.esri.com/watch/45/presidents-award-city-of-frisco_comma_-texas#sthash.Gb5pH9Lj.dpuf.) On the way to a fire scene, a variety of information is provided to first responders, including maps, arrangement of the fire lanes, the location of fire hydrants, and pre-plan information with site details. Specific details include information on the location of standpipes, how the building was constructed, the building layout and room functions, annotations on any recent problems, a list of hazardous materials in the building, up-to-date emergency contact information, real-time video camera information from within the target building, as well as available water lines and capacity. This type of system provides a model on how information can be tapped for fire fighter and civilian safety.

A popular descriptive phrase used in today's common lexicon is "big data," which is indicative of the systematic use of the information being leveraged in ways that were unimaginable a short time ago. Before 2013, fire inspections in New York City were paper based. All that changed when FDNY's Analytics Unit got rolling. There are about 330,000 buildings in the inspection portfolio in New York City, with about 10 percent inspected annually. To address the question as to which buildings ought to be inspected, Jeff Chen and Jeff Roth put together "FireCast," a data-driven predictive risk engine [24].

Dispensing with a reliance on causation in favor of correlation, data on every aspect of life in New York City were accessed. This was possible because the city had invested in digitizing and harmonizing whatever data were available, including everything from 3-1-1 noise complaints to sewage back-ups, power outages, building age, sprinkler presence, whether the building was guarded, building permit information, and so on; thousands of independent streams of data were collected. FireCast Version 1.0 was deployed in March 2013 and included about a dozen risk factors; the latest version relates thousands of types of data to determine the relationship with key fire incident indicators.

The risk profile is updated daily and provided to fire inspection teams, who can then decide which properties ought to be inspected. Infraction rates significantly increased with the deployment of FireCast 2.0. The impact of this work is being tracked and is expected to lead to reduced fire losses.

1.6 Steps in the Development of Smart Fire Fighting

1.6.1 Smart Fire Fighting Workshop

In an effort to kick-start the research roadmap for Smart Fire Fighting, a workshop entitled *Smart Firefighting: Where Big Data and Fire Service Unite* was held on March 24–25, 2014, in Arlington, Virginia, as part of a collaborative effort between NIST and the Fire Protection Research Foundation (FPRF) [24]. The workshop established a dialogue among subject matter experts familiar with the unique characteristics of fire fighting and CPS and began to clarify a collective vision of the ultimate research roadmap expected as a deliverable from this project. The workshop brought together experts from diverse industry, educational, and governmental organizations involved in the areas of data, communications, human factors, fire science, and fire fighting. The workshop participants prioritized a series of research needs based on their potential to enhance the safety and effectiveness of the fire service. The results of the workshop are used as input to this document to provide stakeholder perspective on the scientific and technical basis for Smart Fire Fighting.

1.6.2 The Roadmap

This roadmap seeks to identify and address high-priority measurement science research challenges, technical barriers, and related research and development gaps that hinder widespread application of Smart Fire Fighting technologies and systems to enhance building and community fire protection. There is a growing realization that Smart Fire Fighting can revolutionize today's fire service, making fire fighters more effective and efficient, positively influencing their safety and health, and generally supporting progress in resolving the overall fire problem.

The roadmap is divided into three major sections, each comprising several of the core chapters (Chapters 2 through 12). The first section, Chapters 2 through 6, addresses data gathering and includes chapters on communication technology and delivery methods, sensors (fire fighter on-board sensors, mobile sensors, and stationary sensors), and databases, including existing and emerging data collections. The second section, Chapters 7 and 8, deals with data processing issues, including hardware and software and real-time data analytics. The third section, Chapters 9 through 12, deals with the idea of targeted decision-making data with a focus on end-use applications and user-delivery methods. Chapters 13 and 14 summarizes the roadmap and provides recommendations for future research.

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SECTION

2

CORE CHAPTERS

CHAPTER 2

Communications Technology and Delivery Methods

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Keywords

communication
communication technologies
data
networking

Abstract

The chapter discusses various communication technologies and systems to enable Smart Fire Fighting. Smart Fire Fighting in the future will involve smart sensors and communication devices, and together they will constitute a fully functional distributed cyber-physical system (CPS). Thus, the predominantly voice-only communications view of today will move to a view in which both voice and data will be reliably communicated using smart devices with multiple radios, seamlessly attaching themselves to various access and networking technologies. This chapter discusses remote communications technologies in the realm of personal, local, and wide area networking. For each realm, the chapter presents the state of practice, highlights current limitations, and discusses leading existing research efforts. The chapter also provides a perceived research priority for remote communications and delivery systems specifically for Smart Fire Fighting.

2.1 Introduction

This chapter is devoted to various communications technologies and delivery methods that can be employed for Smart Fire Fighting. **Communications** play a vital role in obtaining and transmitting real-time situational awareness and for incident command and control. Current methods and operations for communications are principally based upon voice communications using land mobile radios (LMRs). Smart Fire Fighting of the future will require both reliable voice and **data** communications technologies, which includes the ability of smart sensors to work together as a distributed CPS, or for remote sensors to provide telemetry data to other responders or to the emergency operations center. This implies that the communications technology and delivery methods needed should be able to collect and transmit real-time information over a personal area network (PAN), a local area network (LAN), and a wide area network (WAN). The challenge is to identify the most promising technologies and research initiatives that will enable reliable, secure, and cost-effective solutions for meeting all those communications needs.

Over a period of several decades, voice radio technology has evolved from analog to the most current P25-based digital radio trunking systems. However, compared with the evolution of mobile communications and computing technology in the consumer space, advancement in LMR technology in the first responder space has lagged substantially in both price and performance. For example, for transmitting and receiving rich multimedia, P25 LMR systems are still grossly inadequate. Voice-based communication would always stay prominent; however, innovation for the next-generation voice services (e.g., push-to-talk or session-based voice calls) should be delivered as specific applications running on smart devices that have multiple radios that let them seamlessly attach to different access and networking technologies. These networking technologies would include fallback options for LMR using legacy networks and advanced networking using spectrally more efficient packet networks.

The problem of remote data communication for first responders is currently being addressed using mostly vertically integrated solutions. Data-only communication is principally achieved using commercial cellular data or WiFi-based WLAN capabilities. In austere or disaster zones, portable cellular and satellite backhaul–based communications solutions are commercially available but not extensively used for fire fighting. Data interoperability remains elusive despite several efforts to standardize schemas and information flows. The interoperability problem is being solved using ad hoc integration, typically performed by the equipment supplier or the township's IT department. Further, most of the present-day solutions require fire fighters to carry several devices in the absence of smart devices that can support multiple radio, access, and networking technologies.

This chapter is a broad overview of voice and data communications technologies. The overview includes the state of practice, current limitations, and promising future research directions. Data communication using smart devices and sensors would be a key enabler for Smart Fire Fighting. For that reason, this chapter devotes considerably more attention to data communications technologies. A broad spectrum of wireless networking technologies is discussed to cover all possible remote communication use cases for Smart Fire Fighting. These networking technologies are based on several factors, including desired range, bandwidth requirements, availability of infrastructure, security considerations, and the group composition. Specifically, methods for delivering communications services to fire fighters for the following broad uses are discussed:

1. Communications between *equipment carried by the fire fighter*, accomplished using a wireless personal area network (WPAN)
2. Communications between the *individual fire fighter and the unit or team* to which he or she is assigned
3. Communications between *Incident Command and the officers and fire fighters*
4. Communications between the *individual fire fighter and dispatch resources, including other jurisdictions*

2.2 Remote Voice Communications Technologies

The technological method that is arguably most apparent to the public for emergency responder communications is voice radio. The functionality of the personal portable radio evolved from a basic device that initially provided basic response communications over time with a portfolio of technological improvements, it has expanded to more sophisticated fireground communications, such as between incident commanders (ICs), crews, and individual fire fighters.

In today's fire service, the wireless radio approach of emergency responder communication is recognized as an application of LMRs (also known as private land mobile radios or public land mobile radios), and it generally addresses ground-based (nonaerial) wireless radio equipment, including vehicle-mounted equipment as well as portable equipment carried directly by emergency responders. The systems handling LMRs can stand alone or be combined with other fixed communications systems such as cellular networks or public switched telephone networks [1].

Dependable emergency responder communication that is fully interoperable is essential for the health, safety, and well-being of today's civilization. The occurrence of man-made and natural disasters has demonstrated, often through its failure, that the communications network is among the most essential components of the safety infrastructure. Ongoing operability is key not only during extreme events but also during relatively common, low-severity but high-probability emergencies. Incompatibility and inoperability within a fire department, among different departments in a jurisdiction, or between agencies in a regional area can have a devastating impact on the effective handling of an emergency event [2].

The last half-century has produced noteworthy advances in public safety two-way radio communications. These advances were focused on improving equipment operability for efficiency and effectiveness, as well as addressing the broad-scale implementation of the technology that created interoperability and compatibility issues. The evolution of radio equipment included a transition from analog-based equipment to digital equipment due to superior operational and performance characteristics. This, along with a widespread dependence on the technology by today's fire service, has taxed the limited spectrum and required new and innovative approaches to radio communications.

In 1988 the U.S. Congress established an inquiry to obtain recommendations from the end-user community and their suppliers to improve and coordinate the communication system, which led to direct involvement of the U.S. Federal

Communications Commission (FCC). As a result, in 1989 a coalition of multiple federal government agencies and private sector communications organizations was formed, leading to the creation of the Project 25 (P25) initiative [3].

P25 is administratively hosted by APCO International (Association of Public-Safety Communication Officials) and includes a suite of standards for digital radio communications for use by public and private sector communications entities in North America in support of the public safety infrastructure. The overarching goal of P25, which continues to evolve within the APCO framework, is to enable public safety responders to communicate with each other and support enhanced coordination, timely response, and efficient and effective use of communications equipment [3].

In 1995 the FCC worked with the National Telecommunications and Information Administration (NTIA) to establish the Public Safety Wireless Advisory Committee (PSWAC) to assess the communications needs of public safety agencies [4]. This led to the establishment three years later of the National Public Safety Telecommunications Council (NPSTC), a federation of key organizations to organize and facilitate implantation of the recommendations of the PSWAC. Today, the NPSTC includes 15 organizations that provide a unified voice to implement improvements in this arena [5]. The NPSTC helps support efforts to address critical key technical issues and programs, such as narrow-banding (a.k.a., re-farming) of the transmission spectrum, as well as other ongoing transitional efforts implemented by the FCC and others to facilitate technological advancements [6].

2.3 Remote Data Communications Technologies

This section discusses families of wireless technologies in terms of the aforementioned considerations in the context of intelligent fire response. It does not address wired communications because there exists a clear need for mobility in the field that would be hampered by wired connections. In reality, wired connections will likely be used as a component in many of these systems, particularly for facilitating high-bandwidth backhauls (e.g., connecting jurisdictions or connecting fireground devices with cloud data center resources). Therefore, the remainder of this chapter no longer considers and merely assumes the existence of such infrastructure, except where wireless technologies are used to augment or replace it in light of failures or complete lack thereof.

Computing and communications capabilities needed to enable smart data-driven analysis and response to fire fighting across structured and unstructured scenarios vary considerably. The systems have to be able to perform in austere conditions where infrastructure-based communication may be impossible or difficult. This section discusses the current wireless access technologies that enable such communication and their potential use and impact on Smart Fire Fighting operations.

Several wireless **communications technologies** enable communication among mobile equipment. An overview of several networked systems is presented for an understanding of their maturity and applicability for Smart Fire Fighting. Networked systems can be characterized using two main attributes: hops and infrastructure. Hops are the number of intermediate nodes used for end-to-end communication, ignoring gateways and backhauls required to link devices in separate subnetworks. There are single-hop and multi-hop networks. Infrastructure-based networks rely on pre-existing infrastructure for establishing communication. Infrastructure-less **networking** is accomplished in an ad-hoc manner in which nodes communicate with each other without any pre-existing infrastructure. The latter is accomplished by either deploying required infrastructure on demand in the field or using no additional infrastructure and having user end devices communicate directly with each other or act as routers for transferring data between a different set of endpoints. Table 2.1 provides a simplified but revealing characterization of various wireless network configurations. Some or all of the nodes in these networks could be connected by a switch, a router, or a gateway to the Internet or to another wide area network.

Table 2.1 A simplified characterization of wireless networks.

Type of Network	Single-Hop Network	Multi-Hop Network
Infrastructure-based	Cellular, satellite, WLAN (e.g., 802.11/ traditional WiFi)	Wireless sensor networks, wireless mesh networks
Infrastructure-less	WiFi direct, Bluetooth/ZigBee (802.15)	Mobile ad hoc networks (MANET, VANET), multi-hop ZigBee

2.3.1 Cellular

Most ubiquitous cellular networking is a classic example of the hub-and-spoke model, in which several mobile devices use radio frequency (RF) signals to communicate with a cellular tower. This single-hop communication is an oversimplification that would be true only if all the communicating devices were in the same cell. For the purposes of this discussion, all devices are assumed to be in the same cell, which would likely be the case at a fireground, and do not consider the backhauls used to link cells.

Significant growth in the commercial cellular technologies has resulted in spectrally efficient high-bandwidth communication and networking technologies. The modern 4G mobile broadband cellular networks offer high throughput (theoretical data rates of 100 Mbps downlink and 50 Mbps uplink) and low latency (10 ms over the radio link and 50 ms for VoIP application). Furthermore, experiments with future 5G technologies have proven the possibility of achieving even bandwidths of several gigabits per second in outdoor environments. The 5G technology is an area of active current research and development. The European Union Framework 7 METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society) program is an example of the effort to accelerate R&D and deployment for the 5G networking technology [7].

Cellular data networks can be used for internetworking of mobile equipment. Further, with increased mobile computing capabilities, as evidenced by the proliferation of smart handhelds and tablets, it would seem that a combination of mobile computing with cellular connections would be the de-facto standard for remote data communication. While there are advantages to using commercial cellular and mobile computing for networked CPS (such as economies of scale and availability of commercial solutions), there are also some drawbacks. First, cellular coverage is not ubiquitous or may not be available during a large-scale disaster. Second, commercial cellular coverage is shared with the public at large, and in the absence of prioritization of Smart Fire Fighting data, it cannot always be relied on for good data rates or latency. In fact, the opposite often happens during large emergency events as cellular networks become congested by civilians frantically trying to make contact with friends, family, and first responders. Finally, sometimes it may be necessary to create wireless LANs for peer-to-peer data exchange, which is not currently possible using cellular radios without dedicated or portable infrastructure. However, a growing body of research aims to enable direct device-to-device communications in cellular networks and [8] presents the state of the art, opportunities, and challenges in this area. Some key challenges include proper radio power control to reduce interference, device power management to prevent rapid battery drain, and management of secret keys and codes currently held and managed by cellular infrastructure.

Some of the limitations of cellular data networks can be addressed. While existing cellular towers would clearly represent pre-existing infrastructure, there exists a possibility of deploying this infrastructure on demand in the field. Lack of coverage or capacity can be dealt with by portable cellular solutions such as a cell on wheels (COW) and a cell on light truck (COLT). While these solutions are reasonably quick to be deployed, they are expensive and may offer only limited bandwidth depending on the backhaul used to connect to the carrier core network. That may not pose a significant issue for connecting devices within the cell since they may not require connections to outside networks, but connecting jurisdictions and leveraging cloud resources will clearly require stable high-bandwidth backhauls. Typical backhaul technologies used are microwave, communication satellites, and existing wired data links. For priority data, unfortunately, unlike Wireless Priority Service (WPS) [9] or the Government Emergency Telecommunications Service (GETS) [10] for voice calls, there are no mature efforts underway for prioritization of data services. However, NTIA FirstNet [11] when (or if) fully deployed, will provide dedicated bandwidth for emergency first operations, which may address the capacity and prioritization issues.

Wireless local area network (WLAN)–based networking to enable peer-to-peer communications without relying on a backhaul to the cloud is currently only possible using non-cellular technologies. An important exception is Long-Term Evolution (LTE), where LTE-in-a-box solutions can now provide a stand-alone LTE network. These boxed solutions provide authentication and session management capabilities, but both the devices and the boxed solutions have to be pre-configured. Another important advance using LTE is a new infrastructure-less networking standard called LTE-Direct that is part of 3GPP Release 12 and is currently being promoted by the industry [12]. LTE-Direct has a range of 500 m and can enable peer-to-peer and mesh networking.

For remote data communications using cellular technologies, the portable and rapidly deployable cellular-in-a-box solutions will continue to grow. Enabling technologies, such as cognitive radios, that will exploit a mix of licensed and unlicensed spectra, will assist those advances. Availability of national-level spectrum registration databases with real-time interfaces will further ease the spectrum crunch. NTIA FirstNet, when deployed, will also encourage suppliers of these devices and integrated mobile communication and computing platforms to leverage cellular broadband technologies for data communications.

2.3.2 Wireless Local Area Networks (WLANs)

WLANs typically are based upon IEEE 802.11 radio interface and use the Carrier Sense Media Access/Collision Avoidance (CSMA/CA) at the media access (MAC) layer. The ubiquitous WiFi access point–based networks for home and enterprise are the most common examples for such networking. WLANs use public spectrum and WiFi radios, so cost and performance make them an ideal candidate for the wireless networking of mobile equipment. However, the use of WiFi in Smart Fire Fighting operations introduces several challenges, as described next.

The ubiquity of WiFi in civilian devices and public places greatly increases the amount of interference in the spectrum despite the increased coverage. Such interference can result in fire-fighting devices exhibiting poor performance in densely populated areas, especially since civilians tend to use social media (e.g., uploading high-definition video of a blaze) excessively during severe emergencies. However, many fire fighters will likely have personal smartphones or company-owned laptops and tablets that they can use during operations, so methods for alleviating this concern should be a high priority in future research.

Typical WiFi offers greater data transfer rates but also operates on higher frequency bands, leading to signal attenuation issues that limit their range to a few hundred feet. Several techniques can increase this range to support wider-area operations. High-powered directional antennas can achieve ranges of up to 2 km in ideal outdoor conditions. Additionally, WiFi can be used in a multi-hop manner to increase coverage range.

Security of WiFi networks remains a paramount consideration for their potential deployment in emergency response settings. Fire-fighter communications should be secured and access to fire-fighting devices restricted to authorized users. Furthermore, first responders gaining access to civilian networks will improve their communications options and coverage. Enabling a system to share the secret keys required to access a network or at least temporarily authorizing devices could address this. Also, prioritizing authorized emergency data on metropolitan WiFi networks, such as those in New York City, could further improve coverage options for fire fighters and their devices.

2.3.3 Wireless Mesh Networks

Wireless mesh networks are a category of wireless networks in which each node in the network is responsible for forwarding traffic on behalf of the rest of the network. In contrast to most other wireless networks, which require a base station to coordinate and relay communications between devices, these networks can be designed and deployed in a more ad-hoc manner. Many modern instantiations of mesh networks include civilian-operated ones with a decentralized or nonexistent authoritarian body and the capability to add or remove nodes with no impact on the overall system. For example, the MileMesh project aims to deploy a network in Hoboken, New Jersey [13]; the Red Hook Initiative is deploying one in Brooklyn, New York [14]; FabFi has demonstrated mesh networks in Jalalabad, Afghanistan, and Kenya [15]. Some projects also aim to create mesh networks using smartphones, such as the Serval Project [16] and FireChat [17], which has been used by protestors in other parts of the world to communicate when the cellular infrastructure was taken down by opposing governments.

Aside from civilian-operated and academic research-oriented examples, few commercial offerings actually exist that implement mesh networking in a manner usable for Smart Fire Fighting. In particular, most of the highly engineered implementations have been targeted at the defense industry, where network resilience is a high priority and naturally leads to such solutions. This is due in part to mesh networks' highly decentralized nature and lack of a clear business model outside the defense industry that can compete with traditional profit-driven telecom infrastructure. Therefore, a main priority for research in this area is implementing a mesh networking system specifically for fire response. It should provide high degrees of resilience (e.g., failures, interference, signal attenuation), data prioritization, and routing that takes into account personnel hierarchies (e.g., routing relevant data through the incident commander's devices).

WiFi mesh is the most promising technology for creating metro area networks, even dedicated metro area networks for emergency first responders. These networks are cheap to deploy, maintain, and expand as they use public spectrum and mature commercial off the shelf (COTS) technologies. The infrastructure-based state of the art has reached the point where these networks can be rapidly deployed in a matter of hours. Even faster deployments are possible with some pre-configuration and use of self-configuring mesh protocols (e.g., ZigBee). Their portability makes them suitable candidates for structural fires. For nonstructural fires (e.g., forest fires), internetworking of mesh networks using satellite or aerial routers is possible but expensive. However, these technologies will become increasingly more cost effective as they mature. It is fully expected that the networking stack will evolve to address the mobility and handoff issues for peering across heterogeneous networks with disparate radio technologies.

While WiFi mesh networks have enormous growth potential and have started to emerge, they have some serious usability limitations for Smart Fire Fighting. First and foremost is the issue of enabling the coexistence of civilian and emergency response data on the same networks. This requires some secure mechanism for prioritizing fire fighter data as discussed previously. It may also require the coexistence of multiple network implementations using the same underlying WiFi (or different) technologies. IEEE 802.11s provides extensions to the 802.11 standard for mesh networking and proposes a routing protocol inspired by Ad hoc On-Demand Distance Vector (AODV) Routing. Extending this standard, or creating a new one entirely, to specifically support Smart Fire Fighting operations should also be prioritized. As previously mentioned, the routing protocols should take the fire-fighting domain into account. For example, flooding-based techniques may be preferred for broadcast messages such as emergency building collapse warnings while more structured routing techniques may be ideal for conserving bandwidth for lower-priority sensor data. This system should be made adaptive so that it can intelligently respond to changes in the network or application requirements. Initially, these adaptations could be carried out in a more centralized manner, perhaps using a software-defined networking approach. This approach could take into account state information of the network and the various applications' demands to determine an overall network resource allocation to satisfy these demands as best as possible. As an example, Qin et al. [18] takes this approach in a generic Internet of Things application, which closely mirrors a future Smart Fire Fighting operational setting.

Mesh networks deployed by unmanned aerial systems (UAS) can provide wireless coverage without pre-existing infrastructure. For example, a team of researchers at the University of North Texas presented such a system at the Smart-America Challenge Expo in June 2014 [19]. They outfitted several UAS with high-powered directional WiFi antennas and demonstrated the ability to connect them over relatively long (for WiFi) distances to create an on-demand wireless network to facilitate data communications among first responders, impacted citizens, and their devices. Such a system will require even more careful power management as most commercially available nanocopter-style UAS have limited flight times of typically 10–30 minutes. Techniques such as flying the antennas to the tops of buildings, where they can be physically placed without relying on further energy consumption to keep them airborne, could be employed to improve the system. Such systems also require careful positioning and mobility control of the devices to ensure a balance between close range to ensure good signal and long range to ensure wider coverage.

2.3.4 Wireless Sensor Networks (WSNs)

Wireless sensor networks (WSNs) [20] consist of sensor nodes, or motes, with limited power, computation, and communication capabilities. Typically, the number of nodes in a WSN is an order of magnitude higher than in any other network, due to their compact size, cheap design, and required area of sensing coverage. Traditionally, the motes are spread across a sensor field, and sink node(s) are designated that connect to a backhaul, possibly the Internet, that transport sensed data to external server(s) for storage and analysis. Often, the data are transported through multiple hops to reach the sink, so mesh networks share a lot of the same challenges as WSNs. For example, both must address bottleneck nodes through which most or all packets must travel between two network segments. In mesh networks, this is usually just a restriction on bandwidth. However, WSNs are almost always battery powered, so in addition to bandwidth, they must conserve energy to improve longevity of the network. This has been an active area of research for years and will continue to be so, in addition to an area of commercial innovation, as Internet of Things (IoT) device deployments scale up.

Most application-specific WSNs are laid as pre-existing infrastructure such as in Supervisory Control and Data Acquisition (SCADA), IoT, and Smart Cities. WSNs typically are used for structural monitoring (residential, commercial, or civic) and environment and habitat monitoring. Specific details of wireless sensor nodes are not in the scope of this chapter. However, Smart Fire Fighting communications equipment can interface with wireless sensor nodes, so it is important that future roadmaps discuss integration and interference issues when interfacing with WSNs. This is particularly true as WSN becomes part of the pervasive smart city infrastructure through the IoT movement. Currently, the networking and data communications protocols between these networks are limited, and integration between the two networks is only possible using gateway nodes usually hosted on remote infrastructure. Peering across heterogeneous networks with disparate radio technology is currently a major challenge that will need to be addressed to allow interoperation of Smart Fire Fighting technologies, including WSNs.

Some WSNs can be field deployed for on-demand sensing and communication of sensed data. For example, ZigBee-enabled sensors can quickly establish an on-demand mesh network between themselves to facilitate data transfer. In recent years, researchers have explored the concept of using "breadcrumbs" to create mesh networks for carrying firefighter personal protective equipment (PPE) and WSN data through a building to the IC [21, 22]. The breadcrumbs are small networked devices that automatically drop from a fire fighter's belt as he or she moves out of range of the previous dropped device. This creates a multi-hop network for delivering data as well as a dense sensor network that can provide critical information about the path a fire fighter took moving through a building. As such devices continue to be developed and commercial offering starts to appear, special attention should be paid to how the devices integrate with other devices and applications in a Smart Fire Fighting system, particularly from a networking perspective. For example, these devices could self-locate and measure the ambient temperature to automatically send fire fighters re-routing messages if their previous path catches fire at some point.

WSNs also face interesting challenges from a computational perspective in addition to the communications perspective. For example, some WSNs use in-network processing to detect events rapidly or to aggregate raw data to a more compressed form for the sake of saving bandwidth and power. These services can be composed to create novel applications that improve fire fighting. As a preliminary step, research should focus on developing prototype applications to identify primitives required for development. This will allow WSN protocol and service designers to properly abstract the requirements in order to facilitate rapid development and innovation of production-ready applications.

2.3.5 Mobile Ad Hoc Networks (MANETs)

Rapid advances have occurred in the area of self-organizing mobile ad hoc networks (MANETs), which do not rely on any preexisting infrastructure, take into account the mobility of nodes, and autonomously reconfigure in the absence of link failures. A MANET is a type of self-configuring network of wireless mobile devices connected by any number of wireless links. Each node in a MANET is a potential router, and an extensive body of research into efficient MANET routing protocols has resulted in several being commercially available. Examples include routing based upon link-state, flow, or distance vector.

Because each node in a MANET acts as a potential router, the implementation and use of MANETs face many of the same challenges as mesh networks. They also face difficulties in supporting high-bandwidth links (e.g., for live audio-visual feeds), especially between devices many hops away. However, they also face significant power constraints due to the fact that, for portability, most of the devices are battery powered. Therefore, intelligent routing protocols that minimize the number of retransmissions and message copies necessary to successfully deliver a message are crucial. Furthermore, the nodes' mobility creates a unique challenge because their locations are constantly changing, and links are constantly gained and lost. This so-called churn requires highly dynamic protocols to overcome, which further decreases the efficiency of the system due to high overhead. MANETs also may be more likely to contain heterogeneous devices and radios. For example, smartphones are often considered ideal candidates for MANETs due to their programmability, pervasiveness, and inclusion of WiFi radios. Several MANET implementations exist that target smartphones, including the Serval Project [16] and FireChat [17]. However, the heterogeneity of smartphones introduces potential compatibility problems that may prevent some devices from talking to one another directly.

Vehicular ad hoc networks (VANETs) are a form of MANETs used for communication among vehicles and between vehicles and roadside equipment. Emerging VANET capabilities include vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), and vehicle-to-infrastructure (V2I). VANETs have some advantages over other MANETs, such as being better powered (due to having the power to propel a vehicle) and having more computational capabilities (already having computers for on-board diagnostics). They do, however, have one significant challenge that many others do not: high-speed mobility. Radio communications can be greatly impeded by high speeds due to Doppler effects, more rapid node churn, and multipath scatter. To address some of these issues, IEEE 802.11p (WAVE) was proposed. Research into the use of V2x communications in Smart Fire Fighting settings may help improve response times (e.g., better clearing of roads and intersections ahead of a fire truck). It may also help facilitate communications at the scene since many of the techniques for addressing the challenges of high-speed VANETs may also prove useful in networking other high-speed devices, such as drones.

Many researchers have aimed to understand the MANET nodes' mobility models and to improve the efficiency and effectiveness of the associated protocols. For example, knowing the future location of a nearby node can inform another node whether passing some information to it will result in the packet being physically carried closer to the ultimate destination. It can also help plan when to transmit information based on known link qualities of nodes that will be within range at a later time. While this area of research is still ongoing, with great promise for improving MANETs, more relevant research should focus specifically on identifying and exploiting mobility models of fire fighters and other emergency personnel on a scene. The research could also begin to address the intelligent placement of additional nodes (e.g., airborne "drone" relays) to improve connectivity, which could provide a basis for better protocol implementations targeted specifically at the Smart Fire Fighting domain.

2.3.6 Personal Area Networks (PANs)

Various IEEE 802.15–based PANs are now commercially available and used in various devices, including smartphones and sensors. These technologies, which include Bluetooth and ZigBee, provide much shorter ranges and lower data rates than 802.11 but also consume much less power. Therefore, they make ideal candidates for providing Layer 1 and 2 connectivity in WSNs (see Section 2.3.4) and on-body networks for fire-fighter PPE and other such devices.

Bluetooth was defined in IEEE 802.15.1, and ZigBee is built on top of the IEEE 802.15.4 physical layer and media access control specifications. These technologies use unlicensed spectrum in the ISM (industrial, scientific, and medical) band (2.45 GHz or 915 MHz). ZigBee provides data rates up to 250 kbps, and Bluetooth provides data rates of up to 3 Mbit/s, although Version 3.0 + HS can use 802.11 to achieve even higher data rates (up to 24 Mbit/s). Their effective range is approximately 10 m to 20 m indoors; much longer ranges on the order of hundreds of meters are possible under ideal outdoor conditions.

A principal challenge is the interfacing of PAN nodes, which use Bluetooth or ZigBee radios, with other networked equipment. One way to accomplish that is on a peer-to-peer basis, which requires the nodes to support a common network medium. Because PAN nodes are usually low powered and often single purpose, this would typically require the other node to support a PAN network or to include some intermediary node whose purpose is to provide the gateway functionality connecting the two networks. This gateway could take the form of an on-site device, possibly attached to a fire fighter's on-body equipment, or it could be accomplished via a cloud server. In the latter model, data are transferred (typically via 6LoWPAN techniques in ZigBee) through the Internet to a cloud server, where it can then be converted to the appropriate format and transmitted back over a different network to the end point. While hardware to support sophisticated radios has improved considerably, the software stacks needed to support several radios and the ability to seamlessly switch across radios and networks are limited and so should be considered a high priority of future research.

Security is another crucial consideration in PANs, especially since the devices tend to be smaller and low powered, making manual security management more difficult due to lack of interfaces and less cryptographic capabilities. Determining methods for effectively managing secure keys is an important area of research, especially since PANs may be field-configurable with different devices being quickly added to a network for specific scenarios. Another promising possibility is the use of distance bounding, which guarantees that devices are within some range of each other [23].

Due to their low power transmissions and use of unlicensed spectrum, PANs are particularly susceptible to interference and signal attenuation. For example, Bluetooth is known to have difficulty transmitting through the human body and from/to devices in pockets, let alone through walls. Because these radios are available to common consumers and used in inexpensive devices, it is possible that the spectrum they use may experience congestion in a more populated or instrumented area, such as in a smart building or a city. For those reasons, considerations should be taken similar to those for using WiFi in fireground communications.

Other technologies to create PANs include WiFi Direct and near-field communications (NFC). WiFi Direct uses the same WiFi radios in smartphones that typically operate in infrastructure mode, but the devices communicate directly with each other in a peer-to-peer manner. This technology is relatively new, so substantial research and development are required in Layers 3 and above to enable applications relevant to fireground response in which many different devices will communicate across the network. NFC is a very short-range wireless technology (less than 5 cm) typically used in smartphones and point-of-sale systems to transfer data between devices or to recognize special tags that hold data such as credit card information or maps and directories. A significant advantage of this technology is that a powered device can interact with passive tags by inducing a current in the tag with its RF field. This can set up more complex interactions like joining WiFi networks or establishing secure connections between devices. NFC is also relatively new and has not seen much adoption outside simple consumer applications. For that reason, future research could focus on exploring possible relevant fire-fighting applications such as responders downloading a building's floor plans upon reaching the entrance or establishing secure connections with devices.

2.3.7 Software-Defined Radios (SDRs) and Cognitive Radios

A central theme that should emerge from the discussion of various networking technologies is that support for multiple radios, along with the corresponding application infrastructure to support integration of disparate devices, is needed. The current state of the art for supporting multiple radios is by using software-defined radios (SDRs). SDRs use a software-based configuration to program the RF hardware (using a system-on-chip, or SoC) for different waveforms and different media access control (MAC). However, for fire-fighting operations or emergency operations at large, even software-based configuration may be limiting for these devices because it requires manual operation to select appropriate settings (e.g., frequency).

Cognitive radios or cognitive radio systems, which can autonomously detect the most appropriate RF communications links and switch to them, have recently started to emerge. Cognitive radios can identify and utilize all transmitting and receiving possibilities within a vicinity; this capability coupled with infrastructure-less networking can truly enable Smart Fire Fighting operations. Cognitive radios and the related issue of developing the software stack on top of those radios to enable seamless session handovers is an area of active investigation.

Commercial considerations will principally drive the RF interoperability and configurability solutions. The current commercial cellular business model in the United States ties user equipment to a carrier's network, which would inhibit rapid adoption of cognitive technologies. However, advances in these technologies will eventually offer a compelling business case to manufacturers to start adopting the technologies, which will directly help the Smart Fire Fighting ecosystem.

2.3.8 Satellite Networks

Satellite networks provide a robust portable mechanism for quickly establishing communications in the field. By bouncing signals off satellites in orbit back to gateways on the ground, fire-fighting personnel can establish communications with other jurisdictions or remote personnel without nearby dedicated infrastructure. This can be especially helpful when cellular and other dedicated networks are unavailable. Satellite links also have the added benefit of providing highly accurate time information; as with GPS, this time synchronization is crucial for properly interpreting satellite signals.

Satellite communications are limited in terms of the environment in which they can be deployed. First, a ground terminal that connects on-site devices to the satellite(s) in orbit requires an unobstructed view of the sky. Satellite links, much like GPS, will not function indoors and can experience poor performance in areas with physical objects in the way, such as near tall buildings or in forested areas. This is further complicated when the satellite network being used has few physical satellites in orbit, since the ground terminal will have fewer options and thus an increased chance of obstruction. Additionally, weather and particulate matter can affect satellite communications, potentially limiting usefulness during severe storms or in thick smoke. This is an active area of research and development, both industrial and academic, because it directly affects commercial viability of satellite networks for phone, television, and Internet access.

Second, due to the fact that wireless signals must travel to the satellite (which often orbits at a high altitude to maintain geosynchronous orbit) and back down to the ground to connect two end points, satellite communications incur significant latency on the order of hundreds of milliseconds. Therefore, satellite links are more suitable to call-and-response-style voice and video communications, sharing and accessing information, and data telemetry. As space rover operators can attest, real-time remote control of robotics is less advisable over such links. The issue can potentially be addressed using high-altitude solar-powered drones to fill the same role of satellites, as described in Section 2.3.11.

Third, ground terminals require careful setup by trained technicians before they can establish a link with a satellite. This is because they must be carefully pointed as close to the satellite as possible for the best signal. This issue can be addressed with self-aligning ground terminal dishes that use their location (gleaned via GPS) and the known celestial coordinates of the available satellite(s) to coarsely aim in the right direction and then fine-tune based on signal strength from the satellite. Rapid movement makes this impossible for a human technician to address, so mobility requirements should also be carefully considered before satellite links are deployed in fire-fighting scenarios.

2.3.9 Microwave Communications

Microwave networks (operating with interoperability standards like WiMAX) can provide long-range high-bandwidth point-to-point communications. High-power antennas require (near) line-of-sight (LoS) and so can be mounted on top of buildings or cellular towers (supported by back-up generators) to facilitate mission-critical communications backhauls. They are also commonly used as the communications medium for satellite networks. Because these networks are particularly useful during power outages and other scenarios that can render wired networks unusable, research should focus on how to place and operate the antennas that make up microwave networks. This must be done in such a way that resilience of the infrastructure is maximized during emergency uses and should take into account the following factors:

- *Power consumption.* Because microwave antennas require large amounts of power to operate, maintaining operations during outages may require additional logistics such as transporting fuel to keep generators active or even the possibility of using microwaves to wirelessly transmit power.
- *Avoiding obstacles and attenuation.* In-situ deployments will clearly require consideration of obstacles that block signals, but attenuation caused by weather or smoke from fires must also be considered

Microwave networks can also be deployed with mobile units mounted to vehicles or field-deployable towers to gain height and achieve LoS. However, this requires careful setup to ensure as direct a link as possible, including minimal obstacles in between, with the backhaul end point. Furthermore, environmental factors such as precipitation, humidity, particulates (e.g., pollen, smoke), temperature, and pressure can greatly attenuate signals, and features such as bodies of water can lead to multipath signals that operators must take into account. Future research should focus primarily on the feasibility of and training required for enabling rapid field deployment, including semi-automation of positioning and pointing microwave antennas.

2.3.10 Ultra-Narrowband (UNB) Networks

With the increasing penetration of low-cost low-powered devices into the market, various novel wireless technologies are surfacing to provide those devices with suitable communications. Ultra-narrowband (UNB) networks are low-bandwidth, low-power, long-range networks based on small transmitting devices and dedicated base station antennas. As these technologies mature, the possibility for cheaply fitting sensing devices with such uplinks for telemetry can become more feasible.

Research should focus specifically on the following domains:

- *Portability.* Wireless transmissions are affected by movement, in part due to Doppler effects, so efforts to properly categorize and accommodate mobility models of both end devices and base stations (possibly portable, e.g., mounted on fire vehicles) should be considered.
- *Reliable transmissions.* Current UNB technologies do not support duplex communications, so reliable transmission of data cannot be guaranteed, but it can be improved through techniques like retransmission across multiple channels.
- *Device management.* Due to the low-power and uplink-only nature of current devices, monitoring, management, and maintenance should be considered priorities for possible deployments.

2.3.11 Airborne Relay Networks

Recently, several organizations have begun experimenting with high-flying wireless relays that essentially act as ultra-low-orbit (atmospheric) satellites to provide Internet access across a wide area with little infrastructure required on the ground. While most of this technology is aimed at expanding Internet coverage to emerging markets in order to create economic opportunities in developing regions, the fire service could also benefit from this research by deploying similar networks in regions without cellular coverage. For example, the relays could be deployed during large-scale wildfires or after large disasters have damaged cellular infrastructure to provide coverage for fire fighters, sensor devices, and other equipment to communicate over long distances. Below are some example projects exploring this concept and some of the research challenges they need to address.

Google's *Project Loon* [24] aims to place a fleet of high-altitude (20 km) balloons in the stratosphere to provide cellular coverage to those who do not have it. The balloons share LTE technology and spectrum with cellular providers, communicating with base stations on the ground that provide Internet backhaul access as well as other balloons to create a mesh network. The balloons rise or descend to move with different wind currents in the desired direction and can stay aloft up to 100 days.

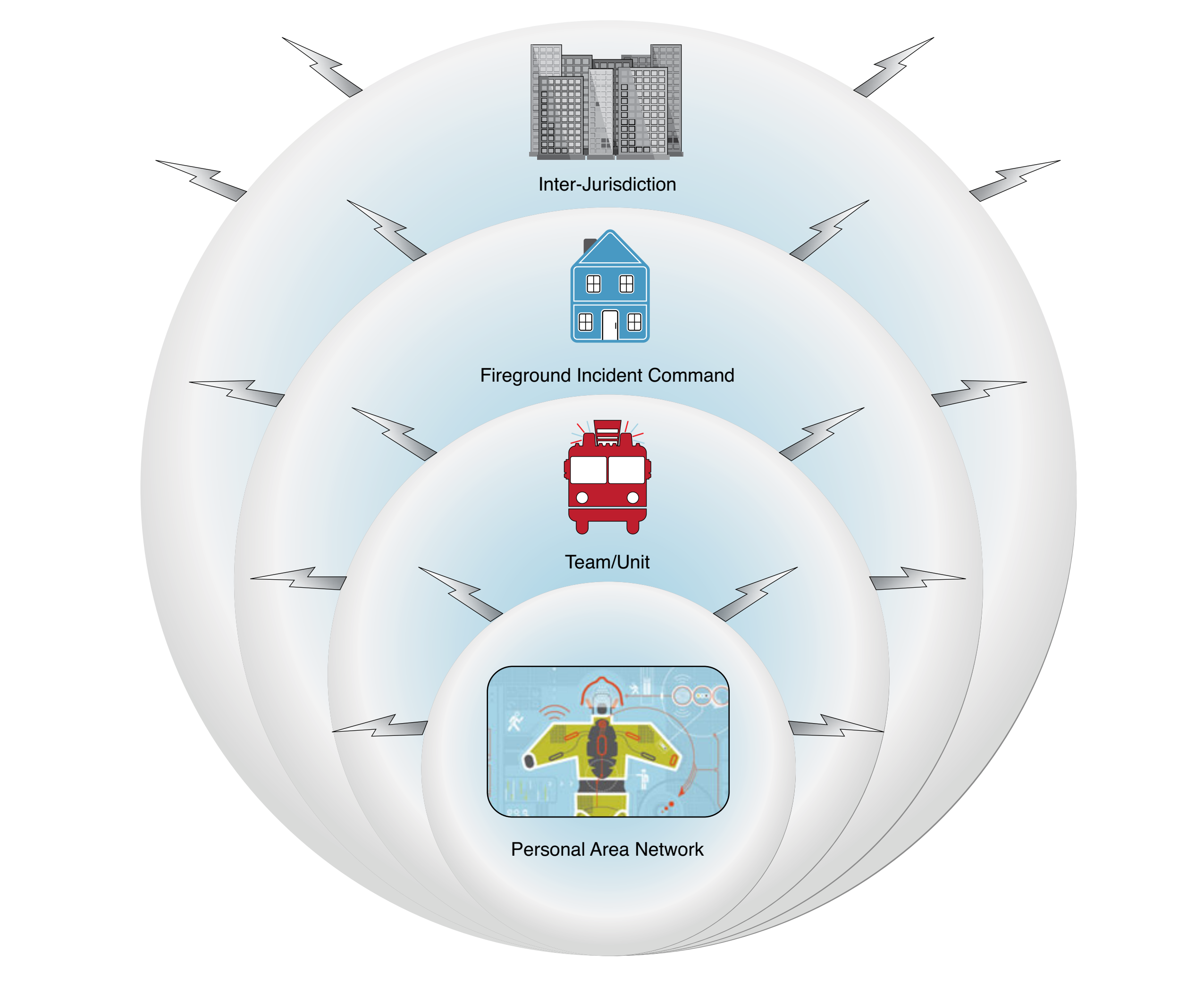
Rather than balloons, Facebook and the Internet.org project aim to use a fleet of high-altitude solar-powered drones. The project hopes to achieve much longer flight times than Project Loon and the ability to better control the flight patterns of their Internet relays. Some of the research challenges they aim to address are outlined in [25].

In addition to using atmospheric satellites for providing wireless coverage, researchers are exploring the use of lower-level UAVs in providing communications using technologies such as WiFi. This is covered in greater detail in Section 2.3.3.

2.4 Overview of Emergency Responder Wireless Communications

This section discusses considerations of various network scopes in Smart Fire Fighting and how the remote communication methods discussed apply within those scopes (see Figure 2.1).

Figure 2.1 Typical communication realms for an emergency event.



2.4.1 Personal Area Networks [On-Board Fire-Fighting PPE and Electronic Safety Equipment (ESE)]

A PAN (sometimes called a body area network) consisting of a "subnet" connecting the various sensors that a fire fighter is carrying provides one communications platform for all of them. Although there is value in having multiple communications pathway methods, in actual practice a single, robust communications platform with a long-duration battery is more likely to be available and functioning when it is needed. The various sensors carried by the fire fighter (camera, temperature monitor, SCBA air-level alarm, location device, etc.) should be managed in a PAN mediated by the primary communications device. Such a system would require a centralized (possibly redundant) computer device to run local applications and manage all the devices and their communications with external entities. It should also incorporate a centralized redundant high-capacity battery to make changing batteries simple and reduce the overall weight of the apparatus. Likely candidate technologies for this system mainly include those used in traditional PANs as well as WSNs for integrating sensor devices.

Regarding the actual sensor data, a significant choice to be made during research and development is what and how much data to keep locally versus transmitting them to a remote location for processing. Clearly, some information should be transmitted to the IC for monitoring the fire fighters' health. However, streaming all the data from the sensors may not be feasible due to bandwidth limitations, power constraints, and intermittent connectivity. Therefore, some data should be stored locally, for later dumping or transmission, which reduces the need for over-the-air usage (and battery drain).

2.4.2 Team/Unit (Fire Fighters)

Peer-to-peer (p2p) communication among a cadre of fire fighters working together as a unit (as small as an engine company operating inside a building or as large as a complete sector of the operation) allows team members to communicate and coordinate with their officers and with each other. A system should support this without interfering with (or being interfered by) outside communications, particularly those used by civilians. Likely candidate technologies to facilitate this scope include WLAN, voice radios, software-defined/cognitive radios, and MANETs. Because these communications often happen at short range and within buildings, particular attention should be paid to ad-hoc approaches that can penetrate dense construction materials and thick smoke as well as maintain high delivery ratios despite rapid mobility of individual devices as fire fighters move through a scene. A simplified method of presenting the data to a company-level officer should be possible.

2.4.3 Fireground Incident Command

When fire fighters work together as a team, they need to be connected to the network that includes the IC. ICs are responsible for organizing a tactical communications network that allows them to communicate with responders for whom they are responsible. The tactical network must be capable of being organized without requiring outside infrastructure (see NFPA 1221, paragraphs 9.3.1.3 through 9.3.1.5). Implicit in this requirement is that any telemetry (e.g., "man-down" alarms, geo-location information, SCBA air-level warnings, temperature), which is of real-time use to ICs or their subordinates (e.g., safety officers), must also be capable of successful operation without benefit of the macro-communications overlay. This data network is in addition to the clear requirement of reliable analog/digital voice communications.

Candidate technologies for this data network include MANETs, mesh networks, software-defined/cognitive radios, airborne relays, cellular, and possibly WiFi. In addition, UNB and WSNs may provide telemetry transport from low-power devices to the IC. Because members of the fire response team will be rapidly moving about the fireground, the emphasis should be on enabling MANETs, especially from the perspective of self-organization and resilience to disruption. Furthermore, future research should focus specifically on how to integrate these multiple types of networks to avoid reliance on a single technology that may fail or become unreliable in a particular scenario. For example, exploiting existing WiFi and cellular networks may help quickly establish communications in a small fire, but larger emergencies will increase the possibility that civilian use will overload those systems, rendering them more of a liability than a benefit to responders. The IC-centric nature of this network can be used as a guiding theme in architecting the overall system. For example, telemetry data from fire-fighter PPE could always be routed through the IC's terminal for central aggregation and use of this information. Other devices may be interested in the data, but they may also require a different radio technology — the central point can act as an ideal choice for placing a multi-radio gateway to link the different networks. However, care should be taken that such a central node in this network be highly ruggedized and ideally duplicated so that it does not become a central point of failure whose fault could disrupt all fireground communications.

2.4.4 Interjurisdiction (Between Communities for Large-Scale Events)

Perhaps the method of communication that comes to mind immediately is voice radio communication between the dispatch agency and the response units. In today's fire service, that function is accomplished using a personal portable radio assigned to individual fire fighters on the fireground and the IC.

The functionality of the personal portable radio evolved from a device that initially was understood to provide only on-scene communications. Over time, with the improvement of the fixed communications systems used by fire departments to which were added voice receivers, comparators, and even simulcast transmitters, it became possible — and expected — that a personal portable radio assigned to a fire fighter would work as a connection to the dispatch center wherever and whenever that fire fighter was assigned.

Additional infrastructure is required to support portable radio use throughout a jurisdiction, due to the relative imbalance between the low-power output and antenna efficiency of a portable radio versus the base station to which it "talks." Each individual portable radio is typically autonomous, usually not relying on any other subscriber units (radios) for its connection back to dispatch or other base locations (e.g., incident command). While the "macro" system that makes the individual-to-dispatch-to-individual connection work, and which is a backdrop to communication technologies relating to emergency responders, it is important to acknowledge that even this large, wide-area layer may be dependent upon local, short-range equipment that extends the macrosystem coverage.

In addition to voice communications, mechanisms for transporting sensor telemetry and other data packets between jurisdictions will be crucial for future Smart Fire Fighting applications. In addition to sharing data between jurisdictions for a more coordinated response to large-scale events, this system could also facilitate aggregating and analyzing data in central servers or data centers for improved situational awareness and decision making. Candidate technologies for this system discussed in this chapter include personal, local, and wide area broadband networks that may include satellite, microwave, cellular, and airborne relays. Additionally, there exists the possibility of creating mesh networks, perhaps using microwave or other long-range antennas, to create the backhauls. Future research in this area should focus on how these networks are planned, built, and maintained by distinct entities so that they maintain operations during highly stressful large-scale emergencies. Data management (i.e., where to send certain streams for further processing) will also play a key role in planning these networks. Therefore, research and development should focus on a holistic approach to these systems because the underlying communications infrastructure should take into account the higher-level overlays and application requirements.

2.5 Perceived Priorities for Research

This chapter has discussed several areas of remote communications and highlighted the current state of practice and areas of future research. Smart computing and wireless networking are both areas of active research — while these efforts would eventually benefit Smart Fire Fighting, an explicit research agenda is needed to address specific fire-fighting requirements, such as improved accuracy, survivability, and low cost of ownership. A research agenda that can ride the commercial wave of development, both for smart computing and for wireless networking, would be ideal. Table 2.2 provides a summary of research priorities for consideration.

It should be noted that it is likely, even in the long term, that wireless broadband networks will not support mission-critical voice for first responders [16]. However, fire fighters are already burdened with a lot of equipment, and they don't want separate devices for mission-critical voice and data communications. Thus, the evolution of the principal communications device to support both mission-critical voice and mission-critical data is the most important research agenda. The current LMR radio devices need to evolve from a predominantly voice-only handheld to a smart device that can adapt and support reliable voice and data communication as a convergent single unit, that is, a single device that can support multiple radios, access, and networking technologies. Further, such an evolution needs to embrace the open apps-based smart computing model of the commercial world. Under such a view, the devices become containers for apps, and developer communities-at-large deliver useful and innovative capabilities via apps to their users.

A second area of research is increasing the reliability and availability of network connectivity, discussed here in the context of local area and wide area networks. A research priority should be robust communications in the presence of interference and/or lack of coverage (e.g., the issue of network congestion and priority in cellular data networks). Germane to this discussion is the rollout of the nationwide LTE-based wireless broadband network dedicated for first responders, called FirstNet. FirstNet, by itself, will never be able to cover all jurisdictions; even in areas covered by FirstNet, there may still be a need for traffic prioritization. A research priority should be to exploit multi-band devices and use of partnering (roaming) arrangements to expand the communications coverage area. Further reliability for local and wide area networking should be achieved using rapidly deployable infrastructure-based or ad-hoc systems discussed in this chapter.

For personal area networking technology, secure and interference-free communication should be a high-priority research item. Interference can be addressed using smart radios and national spectrum database registries. Secure communications require secure key management, and security profiles for Smart Fire Fighting should be a high research priority.

Table 2.2 Research priorities.

Area	Research Priorities	Barriers	Impacts of Success
Communication device	1. Evolve the current LMR-based devices to smart, adaptable, and converged devices capable of reliable voice and data communications across multiple networking and radio technologies	1. Legacy equipment 2. Proprietary systems	Single Smart Fire Fighting device that can provide enhanced real-time situational awareness to the IC and fire fighters
Reliable local and wide area broadband coverage	1. Multi-band intelligent devices that seamlessly roam across networks with roaming arrangements and mutually agreed upon service level agreements (SLAs) 2. Rapidly deployable infrastructure or ad-hoc peer-to-peer networking for remote communications 3. Data traffic prioritization schemes that apply to both FirstNet and commercial mobile networks	1. Legacy equipment 2. Proprietary systems 3. Lack of standards for SLA specification 4. Lack of regulatory mandates for data traffic prioritization	Realizing economies of scale so that cost-effective and reliable systems can be developed for Smart Fire Fighting
Reliable personal area network	1. Smart adaptable radios for PANs 2. Remote key and security profile management of smart devices	1. Lack of concept of operations to take into account smart devices 2. Lack of integration of over-the-air and/or remote management capabilities in the current computer-aided dispatch and joint incident management systems	Plug-and-play integration of certified smart devices as part of joint incident management

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CHAPTER 3

Sensors as Part of Personal Protective Equipment

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Abstract

A key element in the arsenal of tools used by fire fighters is the personal protective equipment (PPE) carried on a fire fighter. PPE is critical to providing protection against their harsh operational environment and allowing fire fighters to effectively implement their assigned tasks. Part of this on-board equipment is their electronic safety equipment that includes, but is not limited to, environmental monitoring, physiological monitoring, sensory support, tracking/location, and electronic textiles. This equipment is an important part of the Smart Fire Fighting landscape.

Keywords

personal protective equipment (PPE)
electronic safety equipment (ESE)
sensors

3.1 Description of Problem

Fire fighters operate in a range of hazardous conditions and severe environments working on a diversity of problems. Fire fighting gear includes both external equipment and also so-called **personal protective equipment (PPE)**, which encompasses the protective gear that a fire fighter dons when undergoing fire fighting activities. PPE should be able to not only protect fire fighters from the hazards associated with their work but also provide data and ancillary information in such a way that the fire fighters are able to do their work more safely and more effectively. Further, the equipment itself needs to be sensitive to exacerbating existing hazards or introducing new hazards (e.g., intrinsic safety of electrical equipment). This chapter details approaches that might be used to develop future generations of fire fighter PPE that would improve the sensor capability of fire fighting PPE while ensuring that the fire fighters can better achieve their work objectives. This chapter is structured around several key elements, including the overall motivation to solve breathing obstacles for fire fighters, the associated historical development of PPE, the mission space for fire fighters, the constraint space of fire fighter PPE, and the current and future sensor system capabilities.

3.1.1 Motivation

Fire fighters regularly encounter hazardous conditions in the course of their work and face difficult decisions about tactics, strategies, and actions associated with any given intervention. Few occupations rely as much on specialized clothing and gear as fire fighting. The most challenging fire fighting environment is the structure fire. In this environment, the fire fighter is enveloped in an extremely hot and toxic environment. Few other occupations subject workers to such inhospitable conditions. Examples in which a worker would immediately perish if the PPE were breached include astronauts and workers operating in deep water. Interestingly, the number of workers in those professions is small relative to the number of fire fighters. In the United States alone, there are over 1 million fire fighters.

While the majority of this chapter focuses on interior fire fighting operations, it should be recognized that fire fighters also have other duties that would benefit from sensor-laden PPE. Fire fighters routinely are involved in emergency medical service work, vehicle extraction activities, brush fire suppression, water rescue work, hazardous materials mitigation, and so forth. Some of those activities require equally specialized PPE and would likely benefit from the considerations presented here.

3.1.1.1 History of Fire Fighting PPE

The basic concept of a paramilitary force dedicated to mitigating fire threats has a long and rich history. Fire fighting crews can be traced to the Roman Empire. For much of fire fighting's long history, fire fighters rarely entered structures to put out fires. Typically, fires were fought from the exterior. In the absence of interior fire fighting operations, there was little need for specialized fire fighting PPE. During the last 100 years or so of fire fighting, there has been a noticeable shift toward interior fire fighting operations. This trend has only accelerated. The evolution of fire fighting tactics has affected the development of fire fighting equipment, just as the evolution of fire fighting equipment has influenced the development of tactics. Early approaches to dealing with the hot and toxic gas–laden environment included the use of heavy insulating clothing that could protect fire fighters during quick forays into a structure fire. To deal with the toxic gases, fire fighters would routinely place bandannas and kerchiefs over the nose and mouth to filter the smoky gas. Helmets were worn to protect them from falling structural elements and from embers that might be falling in the fire. PPE development became more important as fire fighters entered structure fires. Early in the 20th century, fire fighters entering structure fires used tethered breathing lines (Figure 3.1) [1]. Since the mid-1970s, NFPA and other organizations have standardized the design, performance criteria, and testing of fire fighter PPE. NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*, provides the current specification of the state of the art in fire fighter PPE [2].

Figure 3.1 A tethered helmeted fire fighter prepares to enter a structure. (Source: Photograph from the Scottish Fire and Rescue Service Heritage Trust.)

A major technological innovation for fire fighting was the self-contained breathing apparatus (SCBA). Like many technical innovations, the SCBA was transferred from another field and adapted for use in the fire environment. Naval divers required underwater breathing equipment, and the self-contained underwater breathing apparatus (SCUBA) was developed to address that need. NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*, focuses on open-circuit SCBA for emergency responders and details the metrics guiding SCBA evolution [3]. The ability of SCBA technology to revolutionize fire fighting was immediately clear. An unintended aspect to the adoption and adaptation of SCUBA to fire fighting SCBA was the newfound ability and flexibility of fire fighters to proceed much deeper into the structure fire than had previously been possible. The response was the improvement of fire fighting PPE to become thermally more protective. Increasing thermal protection of fire fighter PPE introduced its own set of problems. As fire fighters could proceed deeper into structure fires, it became possible for fire fighters to get into compromised conditions. This could result from the fire fighters becoming thermally stressed by the hot environment and by their physiological activity. In the absence of sensor systems to communicate physiological changes, it is relatively difficult to generally anticipate when significant physiological changes and associated problems might occur. The ability of fire fighters to more deeply penetrate structures also increases the likelihood of exposure to more advanced stages of fire development. Under such conditions, the fire and structure are more likely to undergo negative transitions. One such negative transition is flashover, wherein the upper layer heat flux causes rapid ignition of all fuel packages that have not already begun to burn within the compartment. It is generally acknowledged that flashover conditions can result in severe injury or death, even to protected fire fighters [4, 5].

3.1.1.2 State of the Art

Beyond the previously stated impact of breathing technology (i.e., SCBA) and improved thermal protection, there have been numerous sensor systems either incorporated into or evaluated for use in the standard fire fighting system. One such sensor system of particular value is thermal imaging camera (TIC) technology. Like SCBA technology, TIC technology for fire fighting operations came from technology transfer from defense applications. Adaptation of TICs to the fire environment included the "ruggedization" of the camera package to withstand the even more adverse environments that fire fighters face [6]. TIC technology is now routinely used in various fireground operations: the size-up component of fire fighting operations in which fire fighters attempt to locate the source of a fire; victim location search operations; and the overhaul portion of fire fighting operations in which fire fighters search for fire extension into the void spaces in the walls of the compartment or structure.

Various attempts have been made to develop gas dosimeter systems for fire fighters to use to monitor their overall exposure to contaminants within the structure. Both fire fighters working in structure fires and those working specifically in hazmat operations are generally on air (i.e., breathing using the SCBA) and are not directly affected by a gas environment. One reason to monitor the environment — despite being the use of SCBA — is to understand what chemicals could be contaminating fire fighters' PPE. For hazmat operations, there is generally a post-operation cleaning procedure to detoxify the PPE. This is not a standard process for structure fire operations. Given the recent awareness of the overall toxicity of the product gases that evolve from the burning processes in structure fires and the general concern about the rates of cancer diagnosis in fire fighters, it may be very important to develop dosimeter functionality, particularly for species of concern. Gas dosimetry is extremely important in the overhaul phase, when fire fighters often operate without the use of a SCBA [7].

Efforts have also been made to develop fire transition sensor systems, the most common being monitoring of the potential flashover conditions. Various approaches have been taken to identify transition to flashover. The most common type of sensor system is a heat flux measurement wherein the gauge is used to monitor an effective temperature for the upper layer. Typical flashover heat fluxes are in the 10 kW/m^2 to 20 kW/m^2 range, which is associated with an upper layer temperature of approximately 600°C. By monitoring the upper layer heat flux, it may be possible to use intelligent sensor systems to predict impending flashover conditions [8].

A sensor system that has become ubiquitous in the fire service is contained in the personal alert safety system (PASS) device [9]. The PASS device comprises a sensing system that detects fire fighter motion and an acoustic transmitter that serves as a beacon when the sensing system detects that the fire fighter has been immobile for a predetermined period of time. PASS technology has continued to evolve since its development in the early 1980s. The basic issues in the sensing system detecting fire fighter incapacitation have remained largely unchanged. The acoustic signature of the beacon has evolved with the hope that changes will improve detection and localization of the beacon. The PASS device has become a standard component of SCBA systems. Manufacturers and technologists have been developing and evaluating associated technologies that can support finding fire fighters in need of rescue by building on the base PASS sensing system. A more detailed discussion of the acoustic environment and auditory sensing follows in Section 3.4.2.

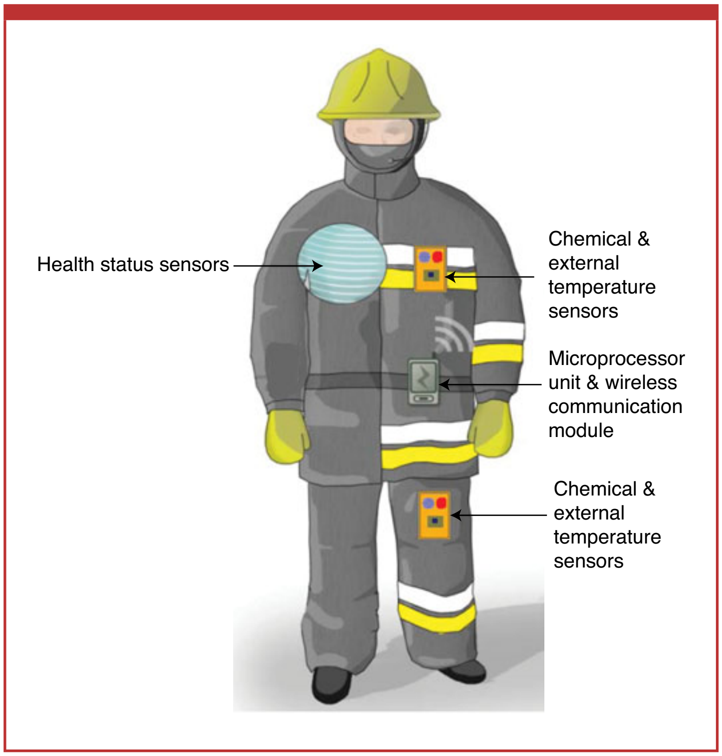
3.1.2 System Constraints

The constraint space of fire fighting PPE has not been explicitly or mathematically specified; instead it has been defined through (mostly) the gradual shifts in overlapping and sometimes disjointed standards. The lack of an overall standard architecture for fire fighting PPE speaks to the level of fragmentation of the technology ecosystem that supports the PPE systems. Relatively new entities with innovations in the different facets of PPE support systems enter the marketplace. Fire fighters and sometimes whole departments adopt technologies that may or may not conform to any particular standard, and in many cases the standards themselves have yet to emerge. As wider adoption occurs, reactive standards are anticipated to be developed to reduce perceived negative consequences of the new technology. To better understand what factors affect the constraint space of fire fighter PPE, it is useful to consider the constraint space for a similar, albeit more technologically advanced PPE system (i.e., astronaut PPE). The typical constraint space issues for astronauts include weight, power, flexibility, durability (including thermal and chemical stability), maintainability, and cost. All sensor, communications, and tool systems that can be incorporated into the astronaut system are required to connect, in a modular sense, with the underlying frame of the system.

3.1.3 Role of Technology in Improved PPE

Material science advancements are often technology drivers and change initiators. In the past decade, it has become apparent that sensor systems operating in a coupled manner (in the sensor fusion sense) are more useful in characterizing an environment than are individual and decoupled sensor measurements [10]. The key requirement in sensor fusion systems is intelligence through modeling. Thus, advancements in sensor systems will be enabled by the development of new measurement protocols driven by material science considerations and the systematic coupling of existing and new sensor systems using advanced and fast modeling algorithms. One picture of the types of capabilities possible in future PPE is shown in Figure 3.2.

Figure 3.2 Schematic of multisensor fire fighter PPE.



In each of the sensor systems that will be described, a summary will be provided on the state of the art and a discussion of emerging engineering science approaches that hold promise in radically changing the state of the art. Before discussing the sensor systems, it is useful to describe the structure fire fighting environment.

3.2 The Fire Fighting Environment and Associated Measurements

One of the critical areas that sensing systems can affect fire fighter safety is through improved characterization of the immediate environment enveloping the fire fighter. Awareness of the gas species within the compartment could affect tactical considerations. Beyond the obvious points raised previously about the toxicity of the product composition, relatively simple measurements could have life-safety implications. As an example, when most fire fighters arrive at a structure fire, the fire is burning in a so-called ventilation-controlled (or underventilated) manner. That means the burning process is limited by the amount of oxygen available in the compartment. Fire fighters routinely fight fires in underventilated conditions. One hazard and transition that can occur in such conditions is the inadvertent opening of doors or windows, which rapidly changes the oxygen concentration in the structure or compartment and triggers an extreme fire event, such as backdraft. With the ability to measure changes in oxygen concentration and propagate those measurements into a likelihood for extreme fire behavior, fire fighters might be better able to anticipate such events and take appropriate action to reduce the probability of an adverse effect. There are many ways to measure oxygen, although it is not apparent that many approaches have been specifically tailored to fire fighting conditions. In the following, we discuss the state of the art in measuring various environmental variables. In all the cases, we will identify differences between measurements of the gas phase environment and measurements on or within the PPE.

The fire fighting environment includes numerous risk factors that can potentially affect health and safety. Direct physical injuries resulting from trips and falls as well as crushing associated with structural collapse or interactions with other debris represent a major category. Continuing efforts to reduce rates of injuries of this nature remain challenging, given the evolving nature of architectural design and its relationship to new types of building materials that are being developed and used.

The thermal environment is readily appreciated. High temperatures of proximate objects and surfaces pose the direct threat of burn injuries. Direct contact and sufficient radiant flux can also result in damage to protective gear and equipment. Conducting the often strenuous activities associated with fire fighting under elevated temperatures further enhances the accrued physiological stress.

Fire smoke itself is a mixture of solid and liquid aerosols, vapors, and gases that result from thermal decomposition and combustion. Many of the resulting species are harmful or toxic from the perspective of respiratory health. While personal filtration devices and supplemental gas supplies are utilized, breaches in those systems can occur. A related concern pertains to the overhaul phase, during which such provisions are not always utilized.

Accounting for the physical location and orientation of individual fire fighters presents an additional challenge. This information is critical to ensuring personal safety as well as the ability of field commanders to manage deployment configuration and efficiency. The smoke optical density can be sufficient to compromise visual acuity and can be further complicated by the lack of ambient illumination through the collateral or purposeful elimination of electrical power systems.

The chemical makeup of the respirable environment results from a combination of complex and coupled factors, including the composition of the structure itself and the other materials associated with the utilities (e.g., plumbing, electrical, HVAC) and furnishings. The building may contain equipment for specialized functions, such as refrigeration, fabrication, materials handling, processing, or packaging. These functions are often accompanied with the local storage of a broad variety of chemicals and materials in gaseous, liquid, and solid phases. The source of ignition, degree of ventilation, and state of evolution of the fire event all contribute to the details of the chemical environment. The components and concentrations are also spatial and temporal variables.

The most prevalent and perceived harmful constituents have been generally identified through a combination of laboratory and field measurements and models [11–15] and the toxicants then ranked relative to published exposure standards [16–18]. The identified compounds have been observed in a variety of fire environments, excluding special cases involving exceptional materials, which in principal receive enhanced attention via material safety data sheets, posted hazard warnings, and ab initio notification of emergency response personnel.

3.2.1 Overview of Toxins

Table 3.1 lists the published exposure standards for a variety of principal toxicants of interest as determined by industrial and occupational health organizations in the United States. The columns to the far right note the distinction in the NIOSH standard between daily shift-averaged, short term, and concentrations sufficient to be of immediate physical danger. It is noted that a CO level below 35 ppm (NIOSH REL) is widely accepted as the limit below which SCBA is no longer required. Several investigations have measured the concentrations of these species under a variety of fire and overhaul scenarios [11–13]. In general, those concentrations exceed the values shown in Table 3.1, including those for short-term exposure and frequently those indicative of immediate danger.

Table 3.1 Exposure standards of selected toxicants. (Source: FS-World.com—*Fire & Safety Magazine*, Firefighter particulate and gas sensor technology, Fall 2014 Edition, pages 52–57. Fumiaki Takahashi, PhD – Case Western Reserve University.)

Chemical	Formula	OSHA[a] PEL[b]	ACGIH[c] TLV[d]	NIOSH[e] REL[f]	STEL[g]	IDLH[h]
Acrolein	C_3H_4O	0.1 ppm	0.1 ppm	0.1 ppm	0.1 ppm (C[i])[c] 0.3 ppm[e]	2 ppm
Benzene	C_6H_6	1 ppm	0.5 ppm	0.1 ppm	5 ppm[a] 2.5 ppm[c] 1 ppm[e]	500 ppm
Carbon monoxide	CO	50 ppm	25 ppm	35 ppm	200 ppm(C[i])[e]	1200 ppm
Formaldehyde	CH_2O	0.75 ppm	0.3 ppm	0.016 ppm	2 ppm[a] 0.3 ppm(C[i])[c] 0.1 ppm(C[i])[e]	20 ppm
Glutaraldehyde	$C_3H_8O_2$	none	0.05 ppm	0.2 ppm	0.05 ppm(C[i])[c] 0.2 ppm(C[i])[e]	N.D.
Hydrogen chloride	HCl	5 ppm	none	5 ppm	2 ppm(C[i])[c] 5 ppm(C[i])[a,e]	50 ppm
Hydrogen cyanide	HCN	10 ppm	10 ppm	4.7 ppm	4.7 ppm(C[i])[c]	50 ppm
Nitrogen dioxide	NO_2	5 ppm	3 ppm	1 ppm	1 ppm[e] 5 ppm[c] 5 ppm(C[i])[a]	20 ppm
Ozone	O_3	0.1 ppm	0.05 ppm[j] 0.08 ppm[k] 0.1 ppm[l] 0.2 ppm[m]	0.1 ppm	0.1 ppm(C[i])[e]	5 ppm
Particulates, respirable	—	5 mg/m^3	3 mg/m^3	—	—	—
Particulates, total	—	15 mg/m^3	10 mg/m^3	—	—	—
Sulfur dioxide	SO_2	5 ppm	2 ppm	2 ppm	5 ppm[c,e]	100 ppm

[a]Occupational Safety and Health Administration (OSHA).
[b]Permissible exposure limit.
[c]American Conference of Governmental Industrial Hygienists (ACGIH).
[d]Threshold limit value.
[e]National Institute for Occupational Safety and Health (NIOSH).
[f]Recommended exposure limit.
[g]Short-term exposure limit.
[h]Immediately dangerous to life or health.
[i]Ceiling (not to be exceeded).
[j]Heavy work.
[k]Moderate work.
[l]Light work.
[m]Heavy, moderate, or light work (≤2 hours).

3.2.2 Particulate Sensors

The fire fighting environment includes a host of aerosol particles that present a respiratory health hazard. The nominal respirable range includes particles spanning diameters from 20 nm to 10 μm [12–19], all of which can be produced in varying degrees under these conditions [20–23]. The penetration of smaller sizes is limited by diffusion in the upper airways, whereas larger sizes are filtered by the cilia. Particles are produced directly as combustion-generated materials, attributable to both flaming and smoldering sources. Physical processes such as structural collapse, explosions, or high pressure releases also generate particles over a broad spectrum of sizes. Deleterious effects attributable to the respiratory uptake of particulate matter continue to be a subject of considerable attention and have been linked to acute and chronic outcomes, including a wide variety of cardiopulmonary diseases [24–28]. Of additional concern is the linkage to cumulative lifetime exposure. While filtration and SCBA can be extremely effective, leakage issues do persist. More important, more recent studies have shown dangerous levels of particulates under overhaul conditions, in which protective respiratory gear often is not utilized [29]. Particles occurring in the range between 20 and 100 nm are designated as the ultrafine component and are the subject of considerable attention due to the process of interstitial translocation and the exceptionally long retention times that result [30–32].

It is important to be able to characterize particulate loading for both direct and indirect ingestion hazards. Exposure to particulate matter (PM) has long been linked to a wide range of health effects, including asthma, bronchitis, cardiac diseases, and short-term increases in nonaccidental mortality. While most fire department standard operating guidelines clearly specify the need to use SCBA-provided air in fire fighting operations, there are times when fire fighters rely on judgment in using their SCBA. Because use of the SCBA impedes communication, fire fighters may choose to be off air in post-suppression and "light" smoke conditions (e.g., during overhaul), in vehicle fire suppression cases, or when directing fireground operations as an incident commander. The ability to measure the particulate loading before going off air could have significant long-term health safety implications for the fire service. There are many different technologies used to measure PM. The oldest and simplest way to measure PM is by filtration and gravimetric analysis; however, that method is not size specific and cannot be used for real-time decision making.

Particle concentrations and exposure traditionally have been expressed in terms of mass concentration [e.g., milligrams per cubic meter (mg/m^3)]. This manner of characterizing aerosol concentrations remains in common practice today, although it does not have a fundamental basis in terms of physiological response. More recent studies have shown that total aerosolized surface area tends to more strongly correlate with adverse health effects [33–35]. Apart from the appropriateness of mass concentration as an exposure metric, the situation presents a challenge because the majority of measurement techniques do not measure mass directly. Currently, three direct-reading mass methods are available:

1. Beta attenuation monitors
2. Tapered element oscillatory microbalances (TEOM)
3. Quartz crystal microbalances (QCM)

Beta attenuators are not widely utilized, due to the decreasing popularity of radioisotopes, detector requirements, and issues of absolute accuracy. TEOM instruments are extremely accurate, although they are physically large and mechanically delicate. One portable TEOM is currently available, but it is rather massive and expensive for general use [36]. QCMs continue to evolve, and a number of devices are emerging that are produced via advanced microelectromechanical system (MEMS) fabrication techniques [37, 38]. A downside of the QCM is the limited dynamic range and requirement for the particles to adhere to the actuator. Practical provisions for cleaning and calibrating for reuse remain outstanding, although the ability to replicate devices inexpensively enough to be disposable may become possible.

Aside from the metric used to describe aerosol concentration, particle size remains important insofar as respirable uptake, deposition, retention, and ultimately the adverse health effects that result. Even for laboratory instrumentation, there is no single device for resolving particle size distributions over the entire size range of interest. As such, the prospects in the near term for providing such capability in handheld or integrated sensors are likely to remain somewhat limited. The two most tractable devices are optical particle counters (OPCs) and optical scattering photometers. OPCs count and size individual particles and are available as handheld units with lower detection limits on the order of 300 nm. Optical photometers detect light that is scattered from an ensemble of particles, from which integrated properties (e.g., mass or surface area concentration) can be inferred. The resulting accuracy is influenced by variations in the underlying size distribution, although the optical geometry can be optimized to reduce the uncertainty if the ranges in the peak and the width of the anticipated distributions can be bounded a priori [39]. The accuracy of both OPCs and photometers is affected by variations in the optical properties of the aerosols themselves. The large variability in the types of particulate matter encountered in fire fighting environments introduces additional challenges in designing optical sensors and in interpreting the resulting data. Recent advances in integrated photonics technologies developed for optical storage media are enabling the development of sensors that are suitably compact and low cost to allow integration into existing protective gear [39]. Ultrafine particles are impractical to measure directly by optical methods due to their weak scattering and absorption cross-sections. A number of small differential mobility analyzers (DMA) have recently been demonstrated, affording the ability to characterize the size distribution and concentration with handheld instruments [40, 41].

3.2.3 Gas-Phase Chemical Species

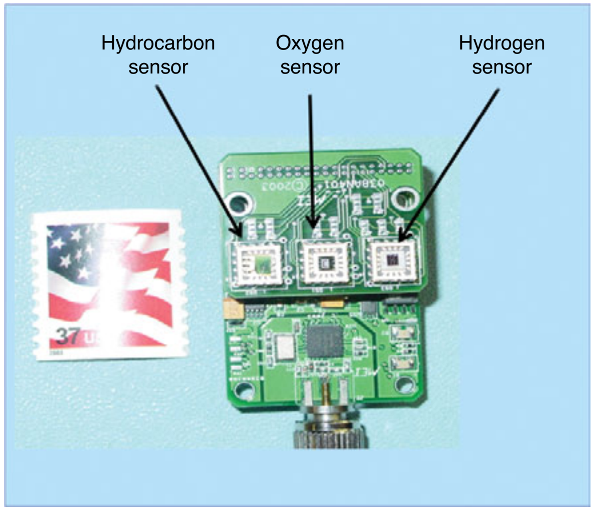
There are various factors relating the measurement of gas phase species to fire fighter safety. As previously noted, by characterizing the evolution and instantaneous values of gas phase species, one has a better sense of the burning process and the overall evolution of the burning process. While an obvious point, it is important to clarify that unless a non-intrusive (e.g., laser-based sensor) is being used, the measurement of the species is often extractive. For extractive measurements, care must be taken to ensure that no reactions occur during the sampling and analysis processes. Other species sensor systems rely on adsorption of the chemical species onto a sensing surface. Ideally, for such cases, a data reduction model or other calibration model should be used to map the surface physio-chemical processes to some estimate of the gas phase composition. For analysis of gas phase species, the classes of measurement systems that have been used for speciation include spectroscopy, metal-oxide semiconductor field-effect transistors (MOSFET) physics, surface acoustic wave (SAW) physics, plasmonic sensing, and oscillating crystal microbalance.

In the context of PPE, several useful distinctions can be made insofar as measuring species concentrations. Laboratory reference instruments such as Fourier transform infrared spectroscopy (FTIR), gas chromatography, and tunable laser absorption and photoacoustic excitation spectrometers can access all the indicated species with high accuracy and discrimination. In principal, it is possible to deploy such devices in the field or acquire samples for post-analysis. However, the distinction is made relative to instruments for use in the field, considering such factors as their mechanical and thermal tolerance, acquisition and analysis time, attendant level of expertise, calibration schedule, and cost for both acquisition and maintenance. Research-grade instruments are clearly invaluable for advancing our understanding of the exposure environment and clarifying requirements for developing embedded sensors. However, they remain largely impractical for field use due to a variety of factors ranging from a lack of real-time response to the inability to log the immediate conditions affecting individual personnel.

The next level of capability is represented by handheld, field-deployable instruments. The physical packaging is suitably robust, and the cost and operational/maintenance issues are within reasonable reach of many fire fighting departments. Some commercially available devices can provide real-time information on selective species, but that is not generally the case. For example, accurate and relatively inexpensive chemical assay tubes are widely available, but they are not capable of providing temporally and spatially resolved data logs of evolving in situ exposure conditions. Continued improvements in the performance of available handheld field instruments can be anticipated, including wider coverage of species, improved accuracy and sensitivity, and wireless data transmission.

That handheld technologies will clearly continue to advance in both form and capability is distinct from the objective of providing sensors that are an integral part of the individual fire fighters' protective and/or life support gear. The prospects for realizing this in practice are coming within reach, due to continued developments in sensor technologies, most notably in MEMS device architectures. A variety of gas sensors have been demonstrated, with the primary types being resistance-based, electrochemical, or Schottky diodes [42, 43]. Surface acoustic wave, plasmonic sensors, and selectively absorptive crystal microbalances are also under development [44, 45]. Extremely small and physically robust devices with favorable sensitivity, dynamic range, and species discrimination are available for a number of target gases of interest, including O_2, CO, SO_2, HCL, and total hydrocarbons, and for humidity. Extremely small overall packages, such as that shown in Figure 3.3, are emerging corresponding to a triplet of gas detectors with an embedded wireless data transmitter. Devices capable of operating at extreme temperatures also have been recently demonstrated [46, 47]. Temperature-tunable sensors have been developed, allowing multiple species to be accessed in a rapid scanning fashion [48]. It should be noted that sensors suitable for the fire fighting environment have special requirements, which may not be accommodated by devices developed for other applications or demonstrated solely in the laboratory with single-component calibration gases. Examples include the ability to maintain performance under high levels of humidity or elevated temperatures. Of particular importance is the presence of a myriad of other background or interfering species. Fire scenarios are especially unique

Figure 3.3 Triplet of MEMS gas sensors with integrated wireless transmitter.



from this perspective, in that the combination of chemical species encountered is virtually limitless and cannot be fully predicted in advance. While it is impossible to test a particular chemical sensor relative to all possible backgrounds, classes of interfering species can be identified.

The barriers to more widespread use of MEMS chemical sensors and the more routine integration into existing protective gear are attributable to several issues. The additive cost to already expensive PPE is certainly among them. Advances in process fabrication will continue to improve this situation, and eventual widespread use would further reduce per-unit cost. This is unlikely to occur until the adoption of performance and interoperability standards, which are required to facilitate the dissemination of both the cost and the complexity of overall system-level functions, such as common power, data logging, communication, calibration, and maintenance. In the form of independent capabilities with redundancies in the above features, MEMS chemical sensors are prohibitively expensive and burdensome to own, operate, and maintain. If approached as an interoperable system, the additive aspects of additional sensor capabilities become increasingly manageable.

3.2.4 Temperature and Heat Flux

While it may seem relatively easy to measure temperature, it should be recognized that there are complexities associated with interpretation of temperature measurements. Because most temperature measurements are indicators of the transducer temperature, it is important that the transducer temperature reflect the temperature of the surface or the medium of interest. Further, as with all measurements, the transducer should not change the temperature or the physics of the underlying system. There are many available transducer systems that can be used to determine temperature. Local temperature can be measured through a variety of physical processes (e.g., electrical resistance, thermomechanical, Seebeck effect). Global or average temperature can be measured using acoustic means, and some laser-based temperature measurements can be made for clean (no particulate matter) gaseous systems. Since some other physical process is being used to infer the temperature, a data reduction model can be used to determine the temperature of interest from the transducer properties and temperature. Additionally, it is important to recognize that the spatial location of the transducer may be imprecise, introducing uncertainty in the measurement location.

Temperature is not generally a particularly useful measurement in the absence of other models used to propagate the measurement into other variables. For example, multiple temperature measurements either spatially or temporally can be used to infer heat flux. Heat flux evolution can be used to determine rate of heating, which is perhaps more useful for forecasting than just knowing a single temperature. For physiological monitoring, a set of point skin temperature measurements can be used to identify thresholds for heat-related stress. A significant amount of work in the wearable technology area is evolving to perform such monitoring exercises. For external temperature sensing, the temperature transducer will typically be mounted on the fire fighter and as such will mostly measure local temperatures near the fire fighter. As previously noted, thermal imaging cameras operating in the infrared portion of the electromagnetic spectrum are useful for charactering surface temperatures of objects at a distance. The accuracy of the measurement depends on many factors, including the presence of a radiatively participating medium between the TIC and the surface of interest, and the emissivity of the object itself. Some thermal imaging camera systems are now being equipped with laser range finders to measure the distance to the object of interest. This works reasonably well when the medium is transparent but becomes less accurate when infrared absorption and scattering occurs along the path length.

In the near future, it is conceivable that wearable technologies with infrared filters will be able to render the temperatures throughout a room and display them on either a heads-up display on the facepiece or some other near-eye lens system.

Several approaches can be used to infer global temperatures in fire environments. This is of value for assessing the overall level of safety within the fire compartment. One approach is acoustic time of flight, which physically determines temperature by way of the change in speed of sound. The possibility of combining local and surface temperature with global estimates offers enormous value insofar as characterizing thermal hazards in compartments.

Heat flux measurements are useful in determining the amount of time available before a surface reaches a critical or threshold temperature. To contrast a temperature measurement with a heat flux measurement, one should note that by knowing even a slowly changing heat flux, one is able to project forward to determine how the temperature will evolve. Heat flux is an important determinant in defining metabolic rates and can be coupled with temperature measurements to identify critical time for the onset of stress.

3.3 Physiological Monitoring and Measurements

A fire fighter's job often involves performing physically demanding tasks under severe environmental conditions, a combination that results in high levels of elevated physiological stress. Fire fighters exhibit a statistically large occurrence of on-the-job sudden cardiovascular events, which remain the top cause of fire fighter line-of-duty deaths. In this regard, physiological monitoring could serve to provide flags for real-time conditions indicating the potential onset of adverse events. In the long term, a better understanding of exposure/outcome correlations could serve to improve the health and safety of the fire fighter population as a whole. Although not directly the subject of interest here, it is noted that the acquisition of personal medical data is a multifaceted issue, drawing a distinction between the available sensor technology and its use in actual practice.

The list of candidate parameters for physiological monitoring is considerable and includes basic indicators of activity levels and physical stress, such as heart rate, skin temperature, and moisture. When an SCBA is being used, quantities such as oxygen and carbon dioxide partial pressures, volumetric flow rate, and gas pressure can also be measured. More advanced device technologies under development include electrocardiogram (ECG) and microfabricated chemical assay capabilities to assess metabolic functions and uptake to certain toxins. Core temperature is often discussed, but nonintrusive measurement techniques have yet to be demonstrated.

Currently, the various sensor types exist at differing levels of technological readiness. Close-to-market physiological monitoring systems are being tested in a variety of conditions [60]. A combination of heart rate, respiratory rate, skin temperature, motion (via a three-axis accelerometer), and ECG has been demonstrated in the form of a wearable garment [49]. The garment also supports the capability for wireless data transmission for the purposes of logging and, potentially, external communication.

A portable unit for metabolic respiratory analysis has similarly been demonstrated [50]. NASA's Portable Unit for Metabolic Analysis (PUMA) measures six components to evaluate metabolic function: oxygen and carbon dioxide partial pressure, volume flow rate, heart rate, gas pressure, and temperature. From those measurements, PUMA can compute the oxygen uptake, carbon dioxide output, and minute ventilation (average expired gas flow rate). The system, which is contained in a relatively small and rugged package, measures critical aspects of an individual's physiological state, including minute ventilation (the average rate of exhaled gas flow), oxygen uptake (the rate of oxygen consumption), and carbon dioxide output (rate of carbon dioxide production). The critical sensors in PUMA are the gas sensors for oxygen and carbon dioxide and the flow sensor. Sinusoidally modulated, blue light from a laser diode excites a ruthenium-based dye at the end of an optical fiber. The dye fluoresces orange light that is phase-shifted relative to the excitation light, and the degree of phase shift is proportional to the oxygen concentration. The carbon dioxide sensor is an infrared absorption technique that uses several infrared (IR) light-emitting diodes (LEDs) focused on a thermoelectrically cooled detector approximately

1 cm away. The LEDs emit light in the range of 4.3 μm, exactly where carbon dioxide has an extremely strong and unique absorption cross-section. Other sensors include a flow sensor, a commercial pressure transducer, a thermistor, and a heart rate monitor. The flow sensor is a commercial ultrasonic sensor custom modified to accurately measure the large gas flows typical in exercise tests. The embedded microcomputer controls and acquires data from all sensors at 10 Hz, performs rudimentary calculations, and transmits sensor signal data wirelessly to a remote computer via Bluetooth. By placing the essential sensors close to the mouth and sampling at 10 Hz, PUMA overcomes timing, sample dilution, and slow sampling issues present on nearly all commercial metabolic carts and portable metabolic units.

A separate class of sensors under development employ more recent MEMS lab-on-a-chip technologies to monitor certain markers of metabolic function. These devices sample subdermal interstitial fluid using disposable micro-needle arrays [51]. On the chip, chemical assay provides access to a variety of metabolic markers, principally blood oxygen, electrolytes, and lactate levels, quantities that can be useful indicators of fatigue, cognitive state, insufficient oxygenation, and severe injury. While these devices are still in the development stage, their use in a broad number of medical monitoring applications is spurring considerable research investment, such that units suitable for practical applications may soon become available.

The effective use of data from physiological monitoring represents a related challenge. Real-time incident command will create an increased demand for integrated medical models, since it is the relationship of multiple quantities that serves to assess the overall physiological state of a given individual under specific conditions. It is noted that accurate evaluation can necessitate individualized baseline data, a situation that invariably raises concerns about the confidentiality of personal medical records. This also applies to the collection of cumulative lifetime exposure data for the purposes of improving the understanding of exposure/outcome correlations.

3.4 Sensory Support

3.4.1 Thermal Imaging

Thermal imaging technology currently relies on the use of focal plane arrays of semiconductor systems that are light sensitive. Thermal noise has been an issue in the resolution available with this technology, but advances in transistor miniaturization and electronic cooling have allowed TIC systems to become significantly more compact [58]. Small-package camera systems are available, and the characteristic length scale is approximately 76 mm (3 in.) and the weight approximately 1.36 kg (1 lb.) Adapting such a system to a fire fighting PPE ensemble would present some engineering technical challenges and obstacles, but examples exist in other applications [65]. Further, it would be useful to be able to display the output on a heads-up display for the fire fighter to see directly without the need to look at a separate screen.

3.4.2 Acoustic Environment

Enhanced auditory capability is not commonly considered to be a need for the fire fighter PPE, but in many scenarios hearing is the most important sense for locating victims or injured fire fighters in a structure fire. Fire fighting is a challenging occupation, with a hostile environment in which fire fighters perform their duties. Many fire fighting activities are performed under extremely loud conditions. Several studies have noted that career fire fighters are more likely than equal-age non–fire fighting cohorts to sustain hearing damage [57]. Hearing degradation poses an unusual stress on fire fighters in performing their search and rescue duties since victims often use voice-based signaling to communicate their location or need for help. Currently, no specific auditory sensing enhancement devices exist for fire fighters. There are interesting challenges, constraints, and opportunities for auditory enhancement devices for fire fighter PPE. One simple improvement that auditory enhancement can provide is noise cancelling using digital signal processing. It may be useful and possible to decrease the overall sound pressure levels associated with common nuisance sounds on the fireground while allowing specific signal types to pass. This highlights a critical interoperability issue that has to be addressed (i.e., the requirement that any modifications to hearing do not interfere with a fire fighter's ability to clearly monitor radio communication). Radio communication is currently the primary mechanism that fire fighters use to interact with commanders and each other. In recent years, there has been a move from analog radio systems to digital radio systems that allow for sophisticated filtering of unwanted and nuisance sounds. While these digital systems generally have worked well, there have been anecdotal cases in which inappropriate filtering affected voice communication. Kushner et al. (2006) investigated the effects of self-breathing noise associated with use of SCBA on radio communication [59]. With the possibility for auditory enhancement, which will likely be based on digital approaches to allow for signal processing, there is the possibility for interference and corruption of the important voice radio communication streams, an issue that will need to be evaluated as the technology evolves.

3.4.3 Haptic and Tactile Information

As fire fighter PPE evolves, it will be possible to incorporate articulation and active exoskeleton components to the system. Exoskeleton additions are being investigated for military applications because these systems afford the ability to perform a wider range of duties with much greater mechanical power. For many types of fire fighting activities, the ability to lift heavier weights or more forcefully pull loads will be an improvement in the overall work effectiveness of the fire fighter. One of the potential negative aspects of powered exoskeleton actuation is the lack of haptic feedback to the human involved in the action to allow for finer control of the effort. One can imagine that a sensor-rich hand system could be used both as a sensor, much in the way our hands are used as sensors. An example of a coupled haptic and sensory glove system is reported by Mrugala et al. [64], who report on the development of a glove system with integrated thermal sensing with vibratory haptic feedback. One can imagine a future in which mobile robots are used in fire search and rescue; in such a future, the sensored hand also might be used to issue commands to the robot agents.

3.4.4 Building Layout Overlays

The increased use of building indoor mapping has created a supply of indoor geometric layouts for structures. With increased use of such mapping and also of building information modeling (BIM), it will be possible for fire fighters operating in a fire environment to get detailed layouts not only of the indoor geometry but also information on utilities within the wall spaces and other construction details. In an extrication activity, a fire fighter with a building overlay dataset and with external tracking could identify where in a particular wall to make a safer and easier cut to enter an adjacent compartment or to exit the structure.

3.4.5 Data Rates for Data Transfer

As we explore the possibilities for fire fighter smart sensing, one immediately notes that many data transfer buses will be required within the PPE system, between the fire fighter and other fire fighters, and between the fire fighter and the outside world. Improvements will be needed in transmission systems and protocols. Consider that Bluetooth data rates are generally in the 1 Mbit/s range and that WiFi (IEEE 802.11) data rates can exceed 1 Gbit/s. Even with these two existing standards, the possibility exists for a significant amount of data transfer. Image resolution, framing rate, and compression algorithms are important factors to consider in delivery of data within the data rates of the transmission system in use.

3.4.6 Heads-Up Displays

Heads-up displays (HUDs) are increasingly used to deliver large amounts of data in image form. HUDs are another military technology that has gained much wider use after translation to commercial products. There are great opportunities in making use of HUDs for fire service operation. One direction that HUDs have moved into is the wearable eyewear space. HUDs will likely be the canvas on which the various sensor data and graphical information are presented. Significant work will be required in the development of appropriate ways for the fire fighter to request the information and for the information to be presented to the fire fighter.

3.4.7 Computational Capability and Architecture

The sensor-rich PPE will require a computing environment to coordinate, assimilate, and fuse the various sensor signals. Further, the computing environment will need to be able to communicate with the fire fighter and allow the fire fighter to request particular elements of the PPE to respond in specific ways. The increased technological capabilities of common consumer products like smartphones will likely be harnessed, improved, and incorporated into a PPE computing systems. One key element of the smartphone system that will be important for PPE development is voice-activated command technology.

Voice activation may be one of the first ways that a fire fighter will be able to control the various sensor systems of the PPE. The central computer will have direct connections with the various sensor systems and will be able to activate certain sensor systems that might normally be in a sleep mode. The central system (PPE brain) will also request, as appropriate, data that can be fused and displayed in a HUD to give the fire fighter information to improve situational awareness. Given the availability of enormous quantities of information, it is important to address the issue of overload and effective interpretation in a real-time environment. The importance of establishing hierarchies cannot be overstated, specifically, ensuring that the most useful information is not overwhelmed in a background of ancillary data.

3.5 Tracking and Location

Because of the hazardous conditions inside a structure fire, it has been an unfortunate part of fire fighting that fire fighters have been regularly injured and killed while performing their duties in structure fires. The interior of a structure during a working fire is a hot and dangerous maze because of the smoke loading and high temperatures. Fire fighters are often unaware of potential hazards within the structure and are forced to navigate within the structure looking for the sources of the fire and possible victims. With improvements in tracking devices, it will be clearer how to determine where fire fighters are at any given time. This will make tactical decisions clearer for incident commanders, allowing them to be better aware of where their agents are and in a better position to relocate those agents as necessary to respond to various threats within the structure. Fire departments use a personnel accountability system to understand which fire fighters are at the site and, in some cases, what those fire fighters are doing on the fireground. One approach is that fire fighters entering the structure pull a tag showing that they are entering the operation. Once they return from the direct operation, they replace the tag, showing that they have been accounted for. It is the responsibility of an incident commander or safety officer to make sure their team makes it out safely. Many different tracking and location technologies have been proposed for the fire service, but no tracking technology has shown widespread acceptance or received a standard use protocol.

3.5.1 GPS, WiFi, and Local RF or RFID Triangulation

A number of technological approaches have been demonstrated for geophysical tracking, each with advantages and with limitations. The following considerations must be addressed in the selection of possible architectures that could be adopted on a broad scale:

1. Resulting range and precision
2. Ability to transmit and receive internal to structures
3. Required infrastructure insofar as both the local transponder and the external network are concerned
4. Cost and maintainability
5. Compatibility or interference with other elements of voice, video, and data communications

The first two considerations are coupled and generally affect all possible approaches to varying degrees. For example, GPS technologies offer high accuracy, have become widely available, and are compact, durable, low power, and relatively low cost. However, the transmitted signals required for triangulation do not generally penetrate into interior structural spaces. This sets aside similar problems affecting the transmission of the geophysical location data to others (both inside and outside the structure) once it has been determined. Variants of enhanced GPS are emerging that attempt to surmount this difficulty with hybrid arrangements of other sensor/transmission types. Two such systems are AGPSS and EGPIS [52, 53], both essentially using triangular cellular phone transmissions to augment during periods of nominal GPS dropout. However, a systematic evaluation of the combined reliability and accuracy of this approach under actual use conditions has yet to be performed. Another technique involves the use of doubly integrated accelerometer data to calculate position trajectories from the point where transponder-based signal dropout occurs. This technology is being utilized in vehicle and accident reconstruction studies, but the applicability here has not been thoroughly vetted.

Because radio communication is now a standard component in fire fighting infrastructure, it is possible to triangulate to provide positional information. Similar issues as described above must be examined to determine the available accuracy and reliability relative to other stations both internal and external to the structure. WiFi communication is much the same, in that the capability is increasingly becoming a standard feature of many structures. Among other issues is the single-point dependence on such a system that could likely be incapacitated by various aspects of the fire situation itself.

Radio frequency identification (RFID) tagging is also possible, although the capability as designed does not directly provide precise geophysical location. Because the tags themselves generally are passive or derive power from the transmitted beam, the available range is relatively limited. As noted previously, a thorough investigation of the capabilities and limitations is lacking. RFID tags can be extremely compact and low cost, making them an attractive option for locating trapped victims, as is done with RECCO tags in avalanche-prone activities [54]. It can be anticipated that this feature may result in the routine incorporation of similar tags into the fire fighters' personal garments.

3.6 Electronic Textiles and Wearable Technologies

Electronic textiles connote a general class of materials that incorporate active component fibers or technologies. On one level, these materials can be used as conductive back planes for power or signal distribution or to form integrated antennas. Electrolytic, piezo-responsive, and tribo-induced fibers are also being explored for both energy harvesting and storage. In contrast, embedded structures can be woven or incorporated directly into these materials to provide various sensor functions. While the connotation is often electrical in nature, optical fibers are also being employed for both distribution and sensing.

Specifically engineered fibers or conditioned terminations have been developed for sensing applications, serving as electrodes or to provide pressure or temperature response [56]. Similar capabilities will likely emerge to provide chemical species detection, addressing a broad range of both physical and environmental sensing. In other instances, the fibers serves as interconnects for integrated nodal components, such as RFID tags, or other microscale components providing sensor, power, or communication functions.

E-textiles and related wearable technologies can be anticipated to provide further enhancements to PPE. This reflects advancements not only in sensor technologies but also in the related areas of power and signal distribution, power generation and storage, and amenities for the closely related areas of communication and geophysical tracking. These technologies potentially offer operational advantages with respect to total garment flexibility and weight, in addition to simplicity in putting on and taking off.

Curone et al. present work on a European Union study on development of wearable technologies for first responders [61, 62].

3.7 Other Considerations

3.7.1 Interoperability and Standards

It is unquestionable that rapid technological advancements in sensors and communication afford unprecedented strides in improving fire fighter safety and efficiency. That being said, the adoption of these technologies in practice largely depends on the adoption of hardware, software, and data standards. These features together speak to the concept of interoperability. The technical and operational issues influencing interoperability are pervasive, encompassing issues involving hardware form factors and interconnectivity, power, data and communication protocols, calibration and maintainability, and ultimately cost. In the absence of standards that will allow these components to be mutually configured, operated, and networked (i.e. interoperated), the incorporation into fire fighter PPE is likely to remain limited. In practical terms, it is unrealistic for each sensor type to be separately procured, operated on different voltages using individualized power sources, be carried independently on the fire-fighting garments, transmit on incompatible transceivers using differing formats and protocols, and be indecently calibrated and maintained.

For a more global discussion of interoperability, the reader is referred to Chapter 7. The design and functionality of interoperable systems, particularly in the forward-looking sense, involve a number of considerations. These are often coupled in both subtle and complex ways, such that achieving more global interoperability is a non-trivial undertaking. As presented in Chapter 7, important distinctions are made between horizontal and vertical interoperability, as well as divisions of scale, that is, the system, the subsystem, and the component levels.

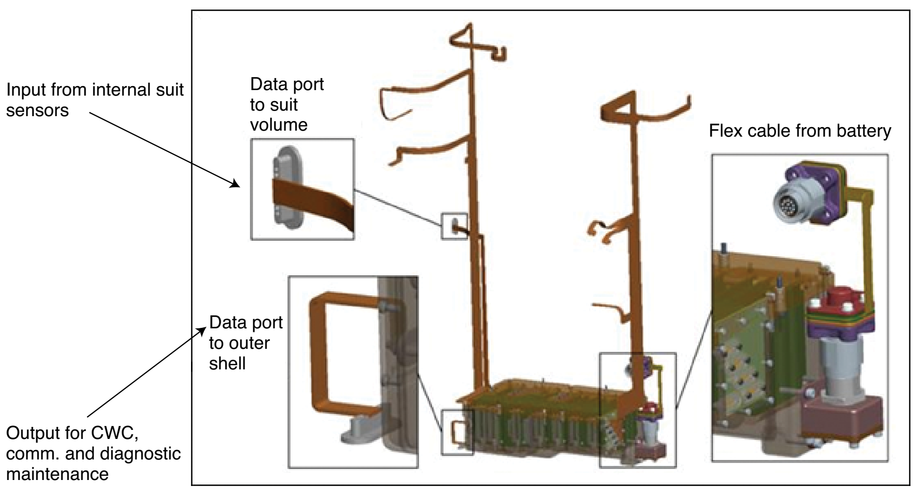
This exerts differing influences on various aspects of the total system, including in the context of PPE sensors the following considerations, as noted above:

1. Operating voltages and centralized power sources
2. Physical package size and method of attachment
3. Pin-outs and interconnects in hardwired systems
4. Communication protocols and frequencies in wireless systems
5. Data formats
6. Procedures for maintenance and calibration

A useful illustration is by way of an astronaut's spacesuit. In this case, margins for weight, power, and reliability drive interoperability as an inherently required feature. All the features indicated above must be designed as components of an interoperable system to meet the operational constraints.

Figure 3.4 illustrates these essential considerations. Shown is a draft concept developed for advanced spacesuit applications [48]. The harness is predicated on a centralized trunk with a common connector for all associated sensors. The system includes a single, common battery for simplified logistics. This consideration simultaneously reconciles issues relating to the center of gravity and thermal environment of the battery. Notice that despite the overt intent to commonize the operating voltages of the individual elements, 30 percent of the available power is nonetheless consumed in voltage conversion. As such, local versus centralized voltage conversion becomes an important consideration. Also included is a provision for a centralized connector for communications, self-diagnostics, and maintenance functions.

Figure 3.4 Concept drawing for interoperable spacesuit sensor, communication, and data system. (Source: EVA Power, Avionics, and Software (PAS) Subsystem Architecture Data Book 2011, National Aeronautics and Space Administration, Glenn Research Center, TD-EVA-PAS-014.)



Sample harness for combined PMAD and data

*In the present EVA architecture study, ≈30% of the total power is consumed in conversion.

Assembly	Phase 3 to 5 Power
Storage	8.72
Informatics	8.97
CWC	7.49
Comm/Nav	9.91
Audio	5.59
PMAD	17.63
Total	**58.31**

≈10 hrs continuous operation using 2.24 kg UHE cell

3.7.2 Intrinsic Safety

With increasing use of moderately high power density batteries and various electrical loads, it has become clear that the very electronic systems used to improve the level of safety for fire fighters in hazardous environments could pose ignition and explosion risks. The language associated with intrinsic safety of electronic equipment is derived from UL 913, *Standard* *for Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II, III, Division 1, Hazardous (Classified) Locations* [63]. In his report *Evaluation of Intrinsic Safety for Emergency Responder Electronic Safety Equipment*, Haase presents the information shown in Table 3.2 indicating the types of **electronic safety equipment (ESE)** that have been evaluated by NFPA. A risk framework should be developed to better assess the requirements for intrinsic safety for fire fighter electronic equipment (e.g., Buchweiller et al. [66]). As shown in Table 3.2, there is wide variation in the level of protection associated with different devices. As new devices are introduced into fire fighting PPE, a consistent approach should be taken in developing standards for intrinsic safety to ensure consistent low risk scenarios that do not unnecessarily hinder technological development.

Table 3.2 Intrinsic safety requirements for typical fire fighter electronic safety equipment.

		Level of Protection									
		Class I (Gases, Vapors, or Liquids)					Class II (Dusts)				
		Group					Group				
Device	NFPA Standard	A Acetylene	B Hydrogen	C Ethylene	D Propane	Temp Code	E Metal	F Coal	G Grain	Temp Code	Class III (Fibers, Flyings)
PASS	1982-7.6	—	—	1	1	—	1	1	1	—	—
SCBA	1981-6.1.8	—	—	1	1	—	1	1	1	—	—
TIC	1801-7.1.4	—	—	2	2	T3, T4, T5, T6	—	—	—	—	—
ESE	1800-7.2.1	—	—	2	2	—	2	2	2	—	2
LMR	TIA-4950				1[8]		1		1	165°C	1

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CHAPTER 4

Mobile Sensors

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Abstract

This chapter overviews existing technologies, gaps, and opportunities with respect to sensors and their associated distributed systems that facilitate fire fighting and emergency response using mobile equipment and apparatus. The technology includes portable equipment, land vehicles, watercraft, aircraft, satellites, and robotic systems. Our discourse is limited to sensors integral to or carried by equipment and apparatus used for fire fighting that is not in physical contact with the individual when operational. The discussion includes various mobile platforms (e.g., manned and UGV, UAV, UUV, and other robotics). When coupled with mobile computing and networking, these mobile sensors evolve to a distributed cyber-physical system (CPS) and we discuss an approach for such an evolution. We present issues regarding data and communications interoperability of these mobile sensors–equipped CPSs and discuss how existing machine-to-machine (M2M) and industrial Internet protocols (Internet of Things or IoT) can be leveraged to address those concerns.

Keywords

mobile sensor platforms
unmanned vehicles
unmanned aircraft/aerial system (UAS)
mobile computing
mobile communications
robotic applications
cyber-physical systems (CPS)
Internet of Things (IoT)

4.1 Use of Sensor Technology Integral to or Delivered by Portable Equipment and Mobile Apparatus

4.1.1 The Problem

Fire fighters and emergency responders use a wide range of portable equipment and mobile apparatus to facilitate their mission. Mobile sensors onboard portable equipment can provide real-time situational information to other fire fighting resources. Sensors and actuators can also play an integral role in remote command and control of the portable equipment. However, the current use of sensor technology is limited and some significant challenges exist, particularly in terms of communication from the sensor/device to a receiving location, storage and processing of data, and delivery of the data to fire fighters and the incident commander. A distributed **cyber-physical system (CPS)** environment, which takes advantage of emerging sensor and mobile communication, computing, and cloud-based technologies, offers a platform for addressing those challenges. To set the context for the role of sensors on portable equipment and mobile apparatus, we begin with a classification of portable equipment and mobile apparatus. We discuss an application architecture that exploits **mobile computing** and mobile networking to bring the full potential of these mobile sensors for Smart Fire Fighting. We then discuss mobile sensor opportunities and challenges.

4.1.2 Portable and Mobile Equipment and Apparatus

Portable equipment encompasses items such as portable pumps, hose/monitor carts, foam units, fans, hand-held gas sensors, hand-held thermal imaging cameras, and life detector units for urban search and rescue (e.g., vibration, camera, sound). Devices that are carried on or that are integral to fire fighter protective clothing for health and safety monitoring (personal protective equipment) and for communication are addressed elsewhere in this report. Likewise, tools for pre- and post-fire assessment, such as cameras, tablets, and smart devices, are not covered in this chapter.

Manned apparatus includes land-based vehicles, watercraft, and aircraft, some of which are used primarily to transport personnel, but most of which are outfitted with equipment used for suppression and rescue operations, such as pumps, hose, and aerial devices. This category also includes specialty land-based apparatus for unique challenges and needs, such as airport/industrial apparatus with foam or dry chemical systems and vehicle-mounted nozzles/turrets/monitors, all-wheel drive apparatus for wildland fire operations, tankers to deliver water, hazardous material, command support, heavy rescue, and so forth. Watercraft includes fire boats (pumpers) and emergency response watercraft. Aircraft include helicopters and fixed-wing aircraft used to transport personnel and to support incident command, as well as those outfitted to deliver chemicals or collect and discharge water on wildland fires. This category also includes equipment integral to or that is attached to the apparatus to perform the target function (e.g., a hose and nozzle attached to a pumper, as the combination is a coupled system).

Unmanned vehicles include unmanned ground vehicles (UGVs), such as wheeled or track-drive fire-fighting and transport apparatus, fixed-wing and rotor-type unmanned airborne/aerial vehicles (UAVs) or drones, unmanned or autonomous surface vehicles (USVs/ASVs), and unmanned underwater/undersea vehicles (UUVs).

Robotics encompasses remotely controlled, self-propelled technology designed for or capable of being used for search and rescue and fire-fighting operations other than as addressed in the discussion on UAGs, UAVs, USVs, and UUVs. This category includes "walking" robots.

A recent trend in terminology involves replacing the term "vehicle" with "system," which is a more comprehensive term and includes other supporting components. For example, "unmanned aerial vehicle (UAV)" is now being indicated in certain arenas as "unmanned aerial system (UAS)." This trend appears to be gaining traction, though for sake of consistency in this report, "vehicle" will continue to be used, with the understanding that widespread use and recognition of this terminology are evolving.

4.1.3 Importance of Mobile Sensors to Smart Fire Fighting

Fire fighters and emergency responders are often faced with making critical decisions with very limited information under extremely stressful situations. Structural fire fighters often face unknowns with respect to where the seat of the fire is, as they cannot see through building components and dense smoke. They have limited communication with pump operators for managing flow rates and pressures on hose lines. Incident commanders often lack a 360-degree view of the fire scene — from outside, including above — as well as inside the structure. Wildland fire fighters, especially support personnel that come from outside of the local area to assist, lack knowledge of the terrain, the vegetation, localized weather conditions, and related factors that can affect the direction and speed of fire spread. Responders to water emergencies may have limited surface and underwater search resources. Responders to chemical, biological, or radiological (CBR) releases or other hazardous material may have sensors with them but limited access to information about atmospheric conditions such as humidity, temperature, and wind direction that could influence spread of the material. In all cases, well-coordinated reporting, processing, and communication of data to inform incident response decisions are lacking.

However, mobile sensors and sensor platforms, whether integral to or carried on portable equipment and mobile apparatus, could be of significant benefit. Field-deployable sensors, integral to or carried by unmanned land, water, or airborne vehicles or robotic systems, can obtain environmental data from locations inaccessible to emergency responders. Data collected by devices that responders carry, such as gas sensors, can be reported remotely to support incident command decisions. Sensors on apparatus that collect and share data on terrain, weather conditions, wind speed, and other such information likewise can help with assessment of potential weather-related impacts, from wind-driven fires in structures to the spread of wildland fires, CBR plumes, and more. Coupled with a geographic information system (GIS) and other data sources on building layouts, street/roadway access, traffic conditions, topography, and more, mobile sensors can become an integral component of Smart Fire Fighting. They can be part of a standalone unit or can interface with other sensor equipment, mobile or fixed smart infrastructure elements, and cloud services to collectively comprise a fully distributed cyber-physical environment.

4.1.4 How the Problem Is Being Addressed Today

Currently, there is significant divergence in the integration of sensors and communication with portable equipment and mobile apparatus. Sensors and communication of data associated with portable fire-fighting equipment, such as pumps and foam systems, appear to be little used. Even though there are several types of portable equipment that collect important fire environment data, from gas sensors to thermal imaging cameras, there appears to be little transmission of data to a centralized location (incident command or other). As such, portable equipment currently can be generally considered “unconnected” in a data communication sense. Even when connected, these systems are based on monolithic traditional client-server designs and are far removed from the plug-and-play interoperable architectures.

Land-based manned apparatus are outfitted with a range of technology to assist in location finding, such as global positioning system (GPS)–type systems. It is not clear, however, that data communication is two-way, taking advantage of telematics technology, transmitting apparatus location to a central location for use in facilitating guidance through traffic, alternative roadways, and so forth. An example is General Motor’s OnStar system. OnStar is a telematics system, a suite of services powered by wireless communications, global positioning systems, and onboard electronics. Telematics systems bring together the capabilities of voice, data, and automotive technology to facilitate Internet and wireless cellular services.

The extent to which vehicle impact detection and avoidance technology is being utilized also is unclear. Watercraft and aircraft have a wide range of location assistance, impact avoidance, and related technologies. However, because such technologies are considered typical for these vehicles, they are not explored further in this chapter. Aside from the location-related sensors, there does not appear to be much in terms of sensor and communication linkages between fire-fighting equipment on the various apparatus, such as between hose nozzles and pump controls for monitoring flow and pressure data. When such information is needed, it is transmitted by voice communication between the fire fighter and the pump operator.

Perhaps the most advanced area within this topic focus is sensors and communication technology associated with unmanned vehicles of all types — ground, water, and aerial. There are two components to these vehicles: control and sensors for support of emergency operations. Vehicle control technology and communication is fairly advanced for ground, surface, underwater, and aerial vehicles. Various technologies support the telematics necessary to guide these devices to locations where they can assist fire-fighting operations, bomb disposal, search and rescue, and incident command via visual data. Cameras are used extensively. In some systems, such as unmanned aerial vehicles (UAVs) for wildland fire support, additional sensor platforms are included. This is a promising area for additional exploration. Several challenges need to be addressed along the way. For example, challenges exist in terms of accuracy of samples while a sensor (platform) is in motion, influences of the vehicle on sensor performance: Does the vehicle cause turbulence, which affects sensor accuracy? Can the vehicle provide appropriate line-of-sight or location-specific (e.g., proximity to fire or chemical release) needs and communications. Other challenges exist in terms of processing and communicating data to appropriate targets (e.g., incident commanders). Those types of challenges are addressed in other chapters. The net result is that while some helpful and some promising systems exist, they, like other systems, operate independently and not part of an integrated CPS.

Another significantly advanced area is use of data from satellite-based systems — GPS, GIS, visible spectrum, infrared (IR) spectrum, and other such data — alone and in combination. Data are available for assisting in response to hurricanes, tornados, floods, and other weather-related events. Telematics applications of GPS technology are widely used in vehicle guidance (as well as robotics guidance). GIS is used to store information regarding structures and contents, and in some jurisdictions, GPS and GIS are coupled to provide information on structures, best available route options, and more to emergency responders. Areas that could be better utilized include satellite imaging in both visible and IR stills (with greater frequency and resolution) and motion. Recent advances in, and increased numbers of, satellites and imaging technology was recently overviewed by IEEE, noting some systems, such as Teledyne’s MUSES approach, can be used for fire detection [1].

Robotic applications, other than as associated with unmanned vehicles, are currently under development for fire-fighting and search-and-rescue operations. This includes development of humanoid-type robots, which can walk, grasp, carry, and pull. Programs such as the DARPA Robotics Challenge [2], the aim of which is to generate groundbreaking research and development in hardware and software that will enable future robots, in tandem with human counterparts, to perform the most hazardous activities in disaster zones, thus reducing casualties and saving lives have facilitated recent development in this area. In addition, swarming robots (ground-based [3] and flying [4]) have been developed and proposed for indoor applications. Significant challenges remain with the humanoid robots across all areas [e.g., walking over rubble and up stairs, grasping small/fragile objects (fine motor skills), driving vehicles]. Challenges exist with swarming robots in terms of interior communication networks for control, communication to locations outside the building, and resiliency to environment.

Robotic applications being developed are purpose-built using mostly vertically integrated solutions. In order to foster an ecosystem of equipment and application providers, it is necessary to create application middleware that will address integration and interoperability across different vendors’ equipment. The problem is being solved using ad hoc integration, typically performed by the supplier or the IT department.

4.1.5 The Parts of the Problem That Can Be Addressed

All aspects of the problem of increasing use of sensors on portable equipment and mobile apparatus are addressable — there are simply different time scales associated with the various opportunities.

Several existing technologies could be utilized in the near-term (the present to three years out). Greater use of telematics, building from OnStar-type two-way interactive technologies and support systems, could help decrease vehicle response time to events. Increased use of unmanned vehicles, satellite imaging technology, and weather and associated data can provide more information for localized (e.g., in and around the building of fire origin) and regional (e.g., monitoring and response to wildland fires) responses. In addition, significant advancement can be made in terms of identifying and integrating sensors and communication technology into equipment. Such integration includes adding communication technology to existing handheld sensors, such as gas detectors, and expanding the availability of wireless transmission of thermal images to a staffed location to assist incident commanders. While these enhancements might continue to be singular points of data in the near term, until integrated into a broader CPS, they will help incident command decisions, and little "new" technology would be needed to realize benefits.

In the midterm (three to six years), increased use of unmanned vehicles can be used to enhance situation awareness by integrating additional sensors. These systems typically include a camera. Temperature, heat flux, or other sensors could be added, allowing for transmission of fire or other environment data. Communications (shielded), sensing (while in motion), and environmental hardening challenges would need to be addressed.

Long-term (beyond six years) opportunities include advancements in humanoid robotics and expansion of autonomous fire fighting, search-and-rescue apparatus. For example, facility-based autonomous apparatus could significantly decrease response time concerns by being available on site at all times.

4.2 Literature Review

4.2.1 Portable Equipment

A limited review was undertaken of sensors on portable equipment that report off the fireground or emergency site. Such systems exist for gas detectors, thermal imaging cameras, and other similar systems. However, these systems appear to be more costly than non-transmitting systems, and no studies were identified that discussed communications challenges, such as interference due to structural systems/building mass or environmental influences. There would seem to be significant opportunities to capture such sensor data real-time at a central location.

A recent study undertaken by Mantech [5] notes that no current commercial off-the-shelf (COTS) portable hazmat sensors meet Department of Justice (DOJ) targets for use by emergency responders in terms of size, response time, and related parameters, aside from the remote reporting issue. It was noted that this is a needed research area.

No information was found regarding use of sensors and communication of data associated with portable fire-fighting equipment, such as pumps, foam systems, hose carts, and so forth.

A relatively new area of development is field-deployable sensors for safety and security. Deployable cameras, for example, are used by military and law enforcement [6, 7]. Field-deployable flashover detectors also have been explored but are not yet available (e.g., [8, 9]).

4.2.2 Land-Based Vehicles

As with most land-based vehicles today, manned apparatus utilize GPS to support navigation. In some instances, telematics applications are used to facilitate shortest routes during traffic and during wildland fire events [10]. The extent to which telematics is used is unknown, but the potential appears to be significant.

Advances in anti-crash detection and control system technology in the automotive area were identified (e.g., [11]) but not as applies to fire apparatus.

No information was found relative to sensor connection between fire-fighting equipment associated with apparatus, such as connection between nozzles and pump controls, or similar applications in which real-time feedback could be beneficial.

4.2.3 Air and Water Craft

As with land-based manned apparatus, GPS and other wayfinding technology is used on manned watercraft. Also used are typical devices for avoidance of underwater obstructions (sonar, depth finders, etc.).

No information was found regarding other types of sensors for emergency response support.

4.2.4 Unmanned Vehicles

A large quantity of literature is available on unmanned ground vehicles (UGVs), unmanned surface vehicles (USVs), unmanned underwater/undersea vehicles (UUVs), unmanned airborne/aerial vehicles (UAVs), associated control technology, sensor technology, and opportunities and challenges related to each. It is not possible to comprehensively review all the literature as part of this effort, so only selected papers and technologies are discussed here; it is highly recommended to review references for more detailed information.

4.2.4.1 Unmanned Ground Vehicles (UGVs)

A wide range of UGV technology is available for fire fighters and other first responders. A good overview of current technology and desired functions for UVs and sensor capabilities can be found in [12, 13]. In addition, various UGVs and robotic applications are overviewed by Chang et al. [14] and Szynkarczyk et al. [15]. These documents overview UGVs for special applications, including military and search and rescue. Note that in these and other publications, unmanned vehicles are often referred to as robots, service robots, or robotic-assisted technology, so there is some overlap with the robotics section of this chapter. However, the primary focus in this section is large UGVs predominantly used for outdoor applications, with smaller, indoor robotic applications addressed in the robotics section later in this chapter.

A number of UGVs for fire suppression are overviewed by Tan et al. [16]. The wheeled and track drive systems they address focus primarily on systems designed to deliver water or other suppression agents. These systems are able to get closer to a fire than people or at least minimize risk to fire fighters. Various GPS and other remote control technologies are discussed, as is hardening of the UGVs for the expected fire environments. Not much is provided on sensors and communications, however.

Miyazawa [17] overviews six models of UGVs and UUVs used by the Tokyo Fire Department: Rainbow 5, Jet Fighter, Robocue, Fire Search, Water Search, and a prototype fire-fighting UGV, some of which are also detailed in the paper by Tan et al. [16]. Various technologies are employed. Jet Fighter, for example, is operated and controlled by a remote user through a wireless communication system and is equipped with a monitoring system and an obstacle avoidance system embedded into its autonomous navigation system [16]. Heat resistance, mobility, power, signal transmission, and autonomy are challenges identified by Miyazawa [17]. Little discussion regarding sensors is provided.

Interestingly, examples of conversion kits to make remotely controlled ground vehicles were found. The Quinetic Robotic Appliqué Kit [18], for example, temporarily transforms a Selectable Joystick Controlled (SJC) Bobcat loader into a remotely operated UGV capable of using more than 80 Bobcat-approved attachments, which could be used to assist transport and search and rescue operations.

Technology also is under development for sensor networks for use with mobile robots for disaster management [19]. Additional discussion on sensor networks for fire and robotic applications are overviewed in the following sections.

Little information was found with respect to fire sensors on UGVs. Amount and quality of data in transmissions, however, could be an area for further development.

4.2.4.2 Unmanned Surface Vehicles (USVs) and Unmanned Underwater Vehicles (UUVs)

There is a significant amount of information about USVs and UUVs in the literature, primarily for military applications. A search using a search engine for scholarly publications (such as Google Scholar) yields a large number of publications across all aspects of USV and UUV design and operation. Likewise, a web search will yield a large number of manufacturers of the UUVs and USVs that are available.

The U.S. Navy UUV Master Plan [20] was found to provide a good overview of capabilities available and being targeted at the time. It is expected that much of the technology, as applicable to fire fighters and emergency responders, would be available for use.

Although there is significant discussion in the literature about USVs and UUVs, little was found specifically for fire service use. The paper by Miyazawa [17] regarding fire robots developed by the Tokyo Fire Department provides a brief overview of that UUV, Water Search, which uses three propellers for horizontal and vertical movement and sonar for finding items in murky water. No discussion was provided on sensor or communication technology.

4.2.4.3 Unmanned Airborne/Aerial Vehicles (UAVs)

Unmanned airborne/aerial vehicles (UAVs), also commonly referred to as drones, have advanced tremendously in the past decade. Inexpensive, lightweight, and easily deployable, UAVs now provide a viable alternative to traditional forms of flight, such as full-scale aircraft and helicopters. Additionally, the inclusion of GPS, inertial measurement, low-cost micro-electromechanical sensors (MEMS), and system-on-chip designs allow autonomous control and management of flight functions. Robust wireless communication technologies with onboard flight control systems allow location referenced flight changes from the ground in real time, while low-latency video transmission supports creation of a first-person view, putting the operator virtually into the pilot seat. These UAVs typically resemble one of several common design variants, including fixed-wing, rotary-wing, and multi-rotary designs.

Modern integrated and embedded systems have scaled the complexity of constructing and operating UAV devices to miniscule levels, allowing common hardware and control topologies to scale between ultra-light aircraft and the size of commercial manned aircraft. Interestingly, the most common airframe variants employed by researchers are derived from the remote control hobbyist community. These UAV platforms strike a reasonable balance between cost, operational complexity, and payload capacity and are therefore the ubiquitous selection of choice in aerial imaging for research purposes. While this hobbyist-driven technology has offered invaluable new perspectives, the operation and workflow inherits many of the incumbent control mechanisms employed by the do-it-yourself (DIY) community, and as a result there is certainly room for improving these systems.

In addition to UAVs for outdoor use, there has been some development regarding indoor applications as well. One example is SensorFly [4], a controlled mobile aerial sensor network platform for indoor emergency response application. The miniature, low-cost sensor platform has capabilities to self-deploy, achieve 3-D sensing, and adapt to node and network disruptions in harsh environments. An indoor fire-monitoring application scenario was used by the developer to validate that the platform can achieve coverage and sensing accuracy that matches or exceeds static sensor networks and provide higher adaptability and autonomy [4].

With respect to sensor technology, there is a strong history of UAV-based fire sensors. This includes the autonomous fire detector (AFD), a miniature electronic package combining position location capability (using GPS), communications (packet or voice-synthesized radio), and fire detection capability (thermal, gas, and smoke detectors) into an inexpensive, deployable package [21]. An AFD can report fire-related parameters, such as temperature, carbon monoxide concentration, and smoke levels via a radio link to fire fighters located on the ground. These systems are designed to be inserted into the fire by spotter planes at a fire site or positioned by fire fighters already on the ground. Getting the sensor to where it is needed is not always easy, especially when delivered by fixed-wing aircraft.

This same concern exists for sensors integrated into the unmanned airborne system platform Ikhana, which incorporates a multispectral sensor [autonomous modular sensor (AMS)], onboard processing and data visualization [wildfire collaborative decision environment (WCDE)], to provide fire intelligence to management teams [22]. Ikhana has autonomous, onboard processing of the AMS sensor data, which allows real-time fire products sensor data delivery to incident management teams on wildfire events and provides color composite quick-look imagery, fire detection shape files, post-fire real-time normalized burn ratio imagery, and burn area emergency response (BAER) imagery. However, the fixed-wing nature and size of the system makes it impossible to deploy within buildings and difficult to manage in close proximity to buildings and infrastructure.

In addition to use for wildland fire, UAV technology is used for other types of disaster management [23], including tornado events [24]. Sensor technology in these systems includes cameras (still and motion), GPS [23], and weather-monitoring sensors [24].

With respect to sensors for fire environments, survivability is important. In that respect, research conducted on sensors for harsh fire environments, including volcanos and outer space applications, at NASA Glenn (e.g., see [24, 25]) illustrate the range of available technologies and where additional research and development are needed.

Wildland fire is addressed in a subsequent section, but it is noted that extensive research has been undertaken on wireless network systems for wildland fire [10, 27–29], which may be pertinent to sensor packages delivered by UAVs to developing wildland fire events.

4.2.5 Robotics

There are a numerous papers on robotics for fire fighting, only a small number of which were reviewed [3, 12–17, 30–36].

The European Union (EU) has funded a program on development of search and rescue robots under the Icarus Project, and the outcome is summarized in various papers [30, 31]. The program encompassed UGVs, USVs, UUVs, and UAVs but also included integration platforms.

VIEW-FINDER [32] is a European project whose goal is to develop robots that have the primary task of gathering data. The robots are equipped with a wide array of chemical sensors, onboard cameras, and laser and other sensors to enhance scene understanding and reconstruction, and the image data are collected and forwarded to an advanced control station. At the base station, the data are processed and combined with geographical information originating from a web of sources, thus providing the personnel leading the operation with in situ processed data that can improve decision making. This project has many correlations to UGV projects discussed.

Other interesting work is related to ground-based swarming robots. The "Guardians" robot swarm [3] is designed to assist fire fighters in searching large spaces. The approach involves swarming algorithms that provide the functionality by which the robots react to and follow humans. The communication system takes advantage of a mobile ad hoc network, which provides the means to locate the robots and the humans, thus allowing the robot swarm to supply guidance information to the humans.

Examples were also found regarding track-guided robots. The Autonomous Fire Fighting Mobile Platform (AFFMP) developed by Khoon et al. [33] is one experimental example. The AFFMP is equipped with basic fire-fighting equipment and patrols through a hazardous site via a guiding track with the aim of early detection and suppression of fire. The AFFMP in this work incorporated flame sensors and an extinguishing system. The intent is that when a fire source is identified, the AFFMP will promptly extinguish the flame using the fire suppression system mounted on its platform. The patrolling movement is guided by a set of lines with the use of a conventional line following algorithm but with the addition of a homing algorithm.

Another example of an indoor robotic search robot that uses a track system for mobility is the RAPOSA system from Portugal [34]. This system is outfitted with a temperature and humidity sensor, gas sensors, and cameras. The sensors measure both absolute and relative humidity from 0 to 100 percent and temperature from 240°C to 1208°C. Gas types that can be detected by the onboard sensors include methane, propane, butane, and other gases that indicate high explosive level, hydrogen sulfide, and carbon monoxide. There are four webcams: two on the front of the tilting arm, providing a flexible field of view to the remote operators; one on the front of the main body; and one on the robot rear. Artificial illumination is provided by low-consumption LED lights installed near the cameras for use in dark environments.

Another robotic application is a small portable unit that can be thrown into a hazardous area, where it rolls around and collects data [35]. In this work, a portable fire evacuation guide robot system was developed that can be thrown into a fire site to gather environmental information, search for displaced people, and then evacuate them from the fire site. Controlled by means of a laptop-sized tele-operator, the robot contains a camera to capture the fire site, sensors to gather temperature data and carbon monoxide (CO) and oxygen (O_2) concentrations, and a microphone with a speaker for emergency voice communications between fire fighters and victims. The design provides high-temperature protection, waterproofing, and impact resistance.

As we move forward, we can look to NIST to help in developing standard tests for fire-fighting robots, a direction in which they are already moving [36].

4.2.6 Robotic Application Architectures

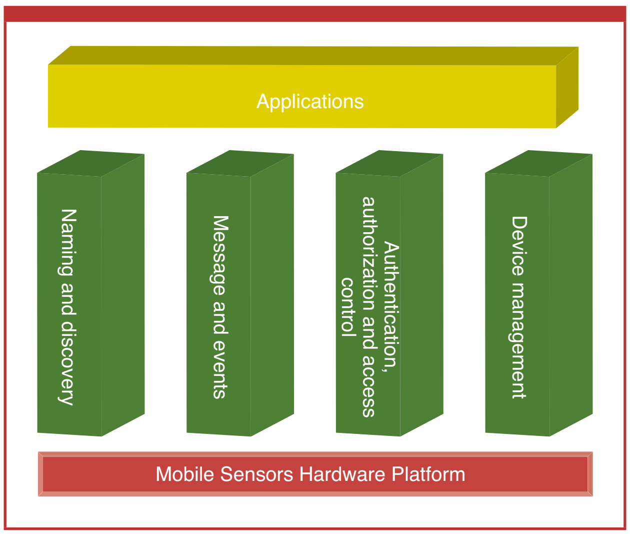
Networking enables various applications and actual utility of the sensors and portable equipment discussed in this chapter can be fully realized only via end-user applications. This section discusses key application platform requirements and the current availability of systems in addition to future trends and roadmap items with specific Smart Fire Fighting requirements in mind. Please note that the remote networking capabilities needed for CPS to enable smart data-driven analysis and response to fire fighting across structured and unstructured scenarios was discussed in Chapter 2. The discussion in Chapter 2 covers a broad range of remote computing and communication capabilities ranging from personal area networks to local area networks to wide area networks.

Mobile sensors and remote actuators available on portable platforms can play an important role in Smart Fire Fighting operations. However, application middleware that can abstract the complexity of underlying sensing, networking, and actuating mechanisms are needed to foster a rich ecosystem of applications developers who can provide user-friendly end-user applications that can integrate and/or interoperate with incident command systems (such as those in emergency operations centers) or with portable commander consoles.

Monolithic applications that are tightly integrated with the systems are slow to evolve, are counter to the current trends of apps and apps marketplaces, and, in the long run, result in delayed introduction of new technologies for Smart Fire Fighting. Enabling an open ecosystem of apps developers and mobile sensors–embedded portable Smart Fire Fighting equipment providers would require defining a framework that could support interoperability of apps and equipment. In the presence of such a framework, one can envision a rich set of Smart Fire Fighting apps that are distributed, adaptable, and can dynamically leverage any compatible mobile sensor within the sensing field.

Figure 4.1 illustrates the core functional elements for such an apps framework. Each functional element is defined, and key challenges in realizing the element for typical Smart Fire Fighting environments are identified. The remainder of this section discusses how the various protocols being developed under the broad umbrella of **Internet of Things (IoT)** [37] can form the basis for realizing an interoperable framework. It should be noted that functional categories represented as vertical blocks are nominal, because their implementations have cross-cutting concerns. This would be evident in the discussion of standards since the same standards address multiple vertical categories.

Figure 4.1 Mobile sensors application stack.



4.2.6.1 Naming and Discovery

A typical fire-fighting scenario may deploy several mobile sensor–embedded portable equipment. Distributed applications that make use of the sensing and actuating capabilities provided by these equipment have to be dynamic and adaptable during fire fighting because manual configuration to enable networking and interoperability can severely limit their usefulness. Thus, mechanisms are needed for these sensors and their services to be named and dynamically discovered by other equipment and applications. For example, a remote sensing application should be able to discover all the video streams from multiple aerial and ground vehicles for a given sensing area and should be able to process and merge those streams to provide enhanced imagery to the incident commander. In fact, many of these sensors and vehicles could be from different manufacturers and with widely different capabilities.

Taking the typical service orientation, these sensors and actuators have to be abstracted as service objects, have to be uniquely identifiable and addressable, should be dynamically discoverable by other services and applications, and need to be monitorable for resilience and recovery. Increasingly these services will be connected using IP transport networks and will make heavy use of the well-established concepts of IP addressing, Dynamic Host Configuration Protocol (DHCP), Uniform Resource Identifiers (URIs), and Domain Name Servers (DNSs). The most robust framework today for making networking of disparate nodes easy is defined by IETF's Zeroconf Working Group [38]. For example, IPv4 hosts are not required to support multiple addresses per interface. Under a MANET deployment and in the absence of reliable DNS and DHCP services, link-local addressing (LLA) [39] becomes important. LLA is part of a standard Zeroconf networking technique. It is important that equipment certification takes into account basic framework support for Zeroconf lest fire fighters end up with monolithic and inflexible systems.

While Zeroconf networking makes it easy for networked devices to communicate, there is still considerable work done to define and describe various sensor and actuator services and their semantics and to understand their data formats. Device-specific vertical efforts exist to define control, data exchange, messaging, and monitoring specifications. The Universal Plug-n-Play (UPnP) forum, for example, defines these specifications for any device at large [40] and for sensor devices specifically [41]. Service orientation is the preferred design framework, and UPnP standards are not fully aligned with OASIS Web Services technology. OASIS's Device Profile for Web Services (DPWS) specification provides implementation guidelines that are more service oriented [42], which makes their reuse and composition by an ecosystem of apps developers easy.

The mentioned standards provide metadata specifications for sensor information exchanges that are well defined by the World Wide Web Consortium (W3C) [43], but more work is needed to create an ontology to describe sensor services across various domains, including biomedical, environmental, home-automation, manufacturing, and industrial. This is important if these sensors services are to be composed to create novel applications both for gathering situational awareness and for remote command and control of devices. Currently a lot of this effort to associate semantics with various sensors is done under the umbrella of the IoT [37]. Several European Union (EU) 7th Framework Program (7FP)–related efforts are examining these composition and other related issues. One specific effort is [44], where the "sensing-as-a-service" concept is getting more infrastructural underpinnings, including semantic representation on these sensor services. Public safety at large can be a key stakeholder for this work and use national forums such as National Institute of Standards and Technology (NIST) and National Fire Protection Association (NFPA) to accelerate research and adoption.

4.2.6.2 Messaging and Events

A CPS consisting of several mobile sensors would require a means for the sensors to exchange data between each other or between themselves and other Smart Fire Fighting infrastructure. Once again, to enable interoperable distributed applications, the framework must provide a uniform abstraction for transport, addressing, and message exchanges. Several device discovery capabilities also provide the ability to monitor, detect, and distribute sensor event data. Specifically, both UPnP and DPWS provide interfaces for event notification besides dynamic discovery and monitoring of these mobile sensors.

Sensors and their capabilities will continue to ride the technology wave, while standards are slow to evolve. To create rich applications that take full advantage of innovations on both sensors and actuators, additional abstractions are needed. The message abstractions have to be suitable for both machine-to-machine (M2M) and machine-to-human interactions. Two efforts, both being leveraged heavily by the IoT effort, are IETF's standardized Extensible Messaging and Presence Protocol (XMPP) [45] protocol suite and the open effort bootstrapped by IBM MQ Telemetry Transport (MQTT) [46].

XMPP is a suite of protocols that started as the Jabber open-source community project to create an open standard for instant messaging but quickly evolved to perform other functions such as collaboration, lightweight middleware for data exchange, content syndication, and message routing. XMPP works over common Internet transport protocol and is thus ideal for creating loosely coupled systems.

While XMPP is suitable for connected smart sensors with capable computing platforms and reliable communication links, there is a need for lightweight protocols for mobile sensors that may have limited resources or may have bandwidth constraints. The resource and bandwidth limitations can be structural, or they can be situational and temporary. In the case of the former, there would be need for applications to dynamically adapt. MQTT [46] is a lightweight publish/subscribe messaging protocol designed for constrained devices and low-bandwidth, high-latency, or unreliable networks.

4.2.6.3 Authentication, Authorization, and Access Control

When mobile sensors are integrated, secure and reliable exchange of messages between them becomes vital. Further, access to sensors during fire-fighting operations has to be governed by roles and privileges. This problem is multifaceted and particularly aggravating for large joint incident command situations where multiple jurisdictions and multiple agencies are involved. What is discoverable and by whom? What sensor services are available and to whom? How are the communication links secured?

There are clearly answers today for those questions. One can conceive of a national credentialing system with tokens or a Command Access Card (CAC) — this technology is certainly available. One can also foresee uniform role and access privilege rules, such as those defined by efforts such as the Department of Homeland Security (DHS) National Response Framework [47]. Further, protocols like XMPP have part of their core specification to support end-to-end encryption to make the information exchange secure. MQTT does not have encryption as part of its core, but it does not preclude use of Secure Sockets Layer (SSL) or the application-specific encryption mechanism. However, the real challenge is not the availability of technology or standards but the impossibility of top-down implementation.

4.2.6.4 Device Management

Device management as a concept emerged with the rapid adoption of mobile communication and the need for mobile operators to manage end-user mobile phones. Most of the standards work in this arena was led by Open Mobile Alliance (OMA), an industry consortium, under the working group for Device Management (DM) [48]. The alliance provides the technical specification for a DM server and a client for management, including over-the-air (OTA), of device configuration and services access. As discussed earlier, the Smart Fire Fighting roadmap should pay critical attention to this capability because it is critical to dynamically reconfigure systems during fire-fighting operations. While OMA DM has several device profiles, future research is needed to understand the device profile for mobile-sensor embedded equipment such as unmanned ground, air, and underwater vehicles. Some of the research challenges include a unified mechanism for disparate platforms and secure real-time and reliable protocols that reliably work in austere environments. While OMA DM can provide the unifying basis, the protocol needs to be extended to support the later requirements.

OMA Lightweight M2M Device Management (LWM2M DM) [49] is, as the name suggests, a lightweight DM protocol for M2M device management in the IoT realm. LWM2M provides device management functionality over the cellular and other constrained communication environments. The standard defines an efficient DM server to client interface using standard IETF protocols such as Constrained Application Protocol (CoAP). CoAP provides extensible Object and Resource model for richer application semantics. OMA also provides a public registry for object registrations.

In summary, DM can enable unified management of a fleet of mobile-sensor embedded equipment. In particular, the OTA capabilities can enable in situ dynamic configuration of devices to meet the operations requirements. Further, this application-agnostic capability can be a lynchpin for enabling on-the-go mobile command and control of these devices, including dynamic updates of credential and policies for information sharing.

4.3 Summary of Perceived Future Trends

4.3.1 Portable Equipment

There are opportunities to integrate remote reporting from portable equipment and apparatus to distributed and central locations to enhance situation awareness and incident response. Real time data to incident commanders can facilitate better coordinated response operations.

4.3.2 Land-Based Vehicles

Enhancements to on-board navigation and route finding can be expected, as well as monitoring of the mechanical state of the apparatus (maintenance/safety needs), crash avoidance systems, and health monitoring of the driver. In addition, connections between components on the apparatus, such as pump controls and nozzle action, so as to provide real time monitoring and adjustment can be foreseen. Development of sensors, communication, and control systems to support these functions is needed.

4.3.3 Air and Water Craft

New and enhanced sensor packages for assisting in wildland fire detection and for support of search and rescue operations (from air or water craft) could be expected.

4.3.4 Unmanned Vehicles

Opportunities exist for advancing automated, semi-automated, and tethered control of unmanned vehicles; for integrating more sensor platforms; for enhancing capabilities for moving through, over, and around debris; for navigating in buildings; and for performing suppression and rescue functions.

4.3.5 Robotics

As with unmanned vehicles, opportunities exist for advancing automated, semi-automated, and tethered control of robotic systems; for developing ground and airborne swarming robots for reconnaissance and perhaps operational support; for integrating more types of and more resilient sensor platforms; and for enhancing capabilities for moving through, over, and around debris and navigating in buildings. Programs by the EU, NASA, DARPA, and others to expand robotic capabilities indicate the broad support for research and development in these areas.

4.3.6 Robotic Application Architectures

Monolithic single-sourced software and hardware–coupled solutions would have to evolve to more apps-centric architectures with protocols and middleware to support plug-and-play integration and interoperability. This, arguably, will be the trend, but its realization might be slow in the absence of proper governance and certification processes. While smart cities infrastructure and IoT efforts will result in mature platforms that support the desired plug-and-play architectures, specific instantiations of these platforms for Smart Fire Fighting or for first responders at large would require a more concentrated effort.

Another foreseen trend is a bottom-up approach for solving the access and security problems for large-scale joint responses. This approach will rely on the following two items: (1) the ability to remotely configure these **mobile sensor platforms**, and (2) the availability of standard information flows during incident responses. Incident commanders, using incident command applications, will use those two items to dynamically provision appropriate certificates, both on mobile sensor–equipped equipment and on the user devices or systems. Mobile computing will be cheap and pervasive; thus, a large number of the mobile sensor–embedded equipment discussed in this chapter will likely have such a capability in the future. Mobile computing coupled with device management capability will help realize the soft dynamic, on-demand configuration of mobile equipment. Standard information flows available as part of the National Incident Management System (NIMS) [50] under the Resource Management and Mutual Aid section will also assist these configuration operations.

A critical future role for NIST or NFPA (or both) would be to clarify design guidelines for the application middleware and provide certification services so that both the users and the developers can benefit from interoperability.

4.4 Technology Gaps, Outputs, and Outcomes in Support of Research

Table 4.1 summarizes the technology gaps to be addressed and the potential outcomes of those successful development efforts. While the table provides a detailed breakdown, note that a fundamental gaps continues to be the ability to equip portal equipment with ruggedized sensors that can reliably communicate with each other and other decision support and incident command systems. Also note that traditional robotics and unmanned autonomous systems are too expensive for fire-fighting requirements. Lightweight and inexpensive drone technology is emerging but is not ready for fire fighting. Further to improve the ability to gather, analyze, and act upon the data from various mobile streaming sensors, there is a critical need of a well-defined application stack to develop fire fighter friendly decision support systems and applications for field usage.

Table 4.1 Technology gaps, outputs, and outcomes in support of research.

Area	Gaps	Outputs & Outcomes	Timeline	Magnitude	Metrics
Portable equipment	Lack of communication structure and protocol for use of data	If it is understood what data are needed, and by whom, communication issues could be addressed	Short-term	Low cost — readily implemented	a. Define incident command data needs b. Beta test on selected equipment c. Assess efficacy
Land-based vehicles	1. Lack of driver health monitoring 2. Lack of crash avoidance 3. Lack of sensors, communication and control between 'end of hose' and pump control and related functions	1. Sensors and systems to help identify symptoms of heart attack and health conditions which might impact driver safety 2. Sensors and systems to further assist in crash avoidance 3. Pump-nozzle sensors, communication and control technology	1. Medium-term 2. Short-term (build on existing tech) 3. Short-term	1. Moderate investment high return potential 2. Moderate investment high return potential 3. Low investment moderate return	a. Develop sensors and systems b. Beta test on selected equipment c. Assess efficacy
Unmanned vehicles	1. Autonomous/swarming UAVs 2. Resilient sensor platforms for harsh environments 3. Robust **mobile communications** technology	1. Minimize exposure of FF to harsh/unsafe environments — speed search & rescue — increase environmental data collection for incident command 2. Increase type and reliability of sensor data in harsh environments 3. Be able to communicate needed information within appropriate resolution and timescale for informing incident command decisions and responses	1. Long-term 2. Medium-term 3. Long-term	1. High investment high return potential 2. Moderate investment high return potential 3. Moderate investment high return potential	a. Develop sensors and systems b. Beta test on selected equipment c. Assess efficacy
Robotics	1. Autonomous/swarming robots 2. Walking, grasping, human-like robots	1. Minimize exposure of FF to harsh/unsafe environments — speed search & rescue — increase environmental data collection for incident command	1. Long-term 2. Longer-term 3. Medium-term 4. Long-term	1. High investment high return potential 2. High investment high return potential	a. Develop sensors and systems b. Beta test on selected equipment c. Assess efficacy

Table 4.1 (Continued)

Area	Gaps	Outputs & Outcomes	Timeline	Magnitude	Metrics
	3. Resilient sensor platforms for harsh environments 4. Robust mobile communications technology	2. Minimize exposure of FF to harsh/unsafe environments — speed search & rescue — increase environmental data collection for incident command 3. Increase type and reliability of sensor data in harsh environments 4. Be able to communicate needed information within appropriate resolution and timescale for informing incident command decisions and responses		3. Moderate investment high return potential 4. Moderate investment high return potential	
Application architectures	1. Leveraging existing frameworks for defining sensor services to create Smart Fire Fighting–specific sensor nomenclature 2. Mission-enabled dynamic adaptation/configuration of networked sensors 3. Middleware for enabling apps ecosystems	1. Families of sensors that are interoperable 2. Make integration of sensors in incident command easy 3. Supplier diversity and innovation	1. Short-term 2. Medium-term 3. Medium-term	1. Moderate investment and moderate return possible. Standardization activity mostly. 2. Moderate investment and high return. Leverage efforts from other sectors. 3. High investment and high return. Non-trivial effort to bootstrap the eco-system	a. Standardization completion b. Beta trials c. Industry uptake

4.5 Perceived Priorities for Research

Areas for further research such as robust remote communication technologies and hardening of the sensors should not be surprising outcomes in light of the technology gaps already identified. There is considerable research focus already on improving the computing and communication capabilities of sensor technologies, and this would eventually benefit Smart Fire Fighting efforts. However, explicit research efforts will be needed to address fire fighting–specific requirements such as improved accuracy, survivability, and low cost of ownership. There is also a critical need for developing a research agenda to develop fire fighting–specific new applications that exploit these highly capable sensors. Fire fighting applications have very unique requirements — for example, they need to be very context sensitive with highly adaptable user interfaces (heads-up display during fire fighting versus tablet for unified incident command).

Table 4.2 provides a more detailed breakdown of perceived priorities for research.

Table 4.2 Perceived priorities for research.

Area	Research Priorities	Barriers	Impacts of Success
Portable equipment	1. Define data needs from portable equipment to enhance incident command (driven from incident command — not equipment) 2. Develop and test communication protocol for high-priority equipment	1. Incident command needs	More robust incident command decisions based on more and better data
Land-based vehicles	1. Driver health monitoring 2. Crash avoidance 3. Sensors, communication and control between 'end of hose' and pump control and related functions	1. Data communications and cost 2. Cost	1&2. Fewer deaths and injuries on fire fighters and other emergency responders in route to incidents 3. More immediate response of water needs at the nozzle — better pump control
Unmanned vehicles	1. Autonomous/swarming UAVs 2. Resilient sensor platforms for harsh environments 3. Robust mobile communications technology	1. FAA — autonomous navigation — environmental resilience — monitoring, command and control systems — cost 2. Cost	Fewer fireground deaths and injuries
Robotics	1. Autonomous/swarming robots 2. Walking, grasping, human-like robots 3. Resilient sensor platforms for harsh environments 4. Robust mobile communications technology	1. Autonomous navigation — environmental resilience — monitoring, command and control systems — cost 2. Fine motor controls — cost 3. Cost	Fewer fireground deaths and injuries
Application architectures	1. Developing sensor services ontologies 2. Developing plug-n-play architectures 3. Developing governance models and middleware to support ecosystem apps developers 4. Apps certification	1. Industry alignment 2. Bootstrapping	Supplier diversity and innovative and feature rich applications that enable Smart Fire Fighting

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CHAPTER 5

Stationary Sensors

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Abstract

Acquiring actionable information from an emergency incident scene is critical for effective fire fighting operations. While the importance of information gathering in emergency response is apparent, the task of compiling that information into authoritative guidance can quickly become perplexing. Unlocking the value of ever increasing data from emerging information technology and cyber-physical systems (CPS) installed in stationary structures and aboard occupant carried platforms requires careful consideration. The complex process of information gathering begins at the sensor. Sensors convert the physical characteristics of systems involved in a fire emergency into information, thereby initiating the process of transforming what is perceived into actionable information. This broad interpretation for sensors can include design modeling tools, devices, or even people. Prior sensor technology success stories for fire safety (e.g., smoke detectors) should inspire the fire community to seek creative implementations of CPS technology. As a starting point, leveraging emerging sensor technologies and installed systems (e.g., building environment) provides latent opportunities (and perhaps challenges) for Smart Fire Fighting.

Keywords

stationary sensors
building information modeling (BIM)
human sensing
modeling

5.1 Description of Stationary Sensors

5.1.1 Overview

Emerging cyber-physical system (CPS) technology, infrastructure, and concepts have increased the availability, utility, and value of information. Currently, sensing (i.e., information acquisition) is being reimagined in stationary structures through a massive proliferation of sensors that provide meaningful information for a variety of interests, including sustainability, energy management, infrastructure health monitoring, and post-9/11 security. The movement away from sensors that alarm and toward sensors that perceive is well on its way. This sensor information supports decision making to optimize function-specific performance. In fact, the accessibility, speed, and integration possible through modern information technology and CPS has expanded the view of information acquisition beyond conventional sensing devices. A CPS information acquisition framework requires carefully curated devices to gather information (device sensing), a facility to use information acquired by people (**human sensing**), and an innovative system to provide context [e.g., geographic information system (GIS) or **building information modeling (BIM)**] for the acquired information. A crowd-sourced implementation of enabled navigation systems is an everyday example of masterful implementation of these elements for wayfinding (land or sea).

Despite sensing innovation in those important functional areas, sensors for stationary structures operate largely in system-specific silos with integration functions currently limited to intrasystem communication on a centralization data network. While the central data monitoring and control network are a first and essential step in integration, the vision of CPS in stationary structures could be fully realized through multipurpose sensors with the functional system (such as fire safety) defined by software intelligence. In the same way that the physical infrastructure is leveraged for varied functions (e.g., the very same door is used for security, energy management, and fire compartmentalization), cyber or sensing infrastructure for disparate systems can be exploited to improve fire fighting, making use of both the central data system and integrated intelligent software.

5.1.2 Problem

When individuals join a fire department, they typically take a solemn oath to protect lives and property within the jurisdiction that they serve. However, in a typical call for assistance, fire fighters often have relatively limited interaction with or data from the people and property that they are sworn to protect. The plethora of static sensors installed for a myriad of comfort, energy management, and security applications are not utilized at all or underutilized for fire safety. Furthermore, the opportunity for people (human sensing) and structures (device sensing) to actively (or dynamically) collaborate to support their own protection is often not being considered. While locations of interest can be gathered from fire alarm panels (fire inspection reports that are filed in local municipalities or information that is to be passed along by occupants and bystanders reporting to call centers), these information acquisition modalities are largely passive (or static) elements supporting the fire department's effective response (with limited capability to affect fire fighter safety). Yet, with the ever increasing sensor-rich environment in which we live, "stationary structures" — those to which the fire department is responding — provide a platform by which valuable data and information could be pushed to fire fighters before, during, and after their response to improve situational awareness and decision making support.

5.1.3 Vision

In the future, **stationary sensors** — that are broadly deployed on scene before fire fighters even begin their response — could collaborate with fire fighters, fire fighter–carried sensors, or building systems and occupants themselves to restore and stabilize the structure and the associated environment. No longer would sensors be relegated to passive elements in response to emergencies, rather they would be active information acquisition tools that are an integral aspect of everyday smart fire service responses, ranging in complexity from the largest high rise fire fighting operation to the daily call for public assistance or emergency medical response. NIST Publication 1130 describes CPS as follows: "A Fire Smart Building would aggregate sensor and performance data from various building systems — including HVAC, elevator, security, fire alarm, sprinkler, occupancy/energy management systems to enable capabilities to visualize the present severity of the incident, forecast future conditions (e.g., significant hazards such as pending collapse or flashover conditions) and monitor and track emergency responders within and around a structure" [1]. This definition provides a glimpse of the necessary evolution in information acquisition from stationary structures that is required to support Smart Fire Fighting needs. A broad vision of sensing comes into view, in which information acquisition would be performed through integrated active device sensing and human sensing. The information would be contextualized using dynamically addressable BIM, in which information is acquired throughout the entire infrastructure life cycle (including design, construction, utilization, and renovation) and is accessible in real time or even super real-time for collaboration with the fire service preceding (years to minutes) a possible emergency response (pre-event), during an emergency response, and after (minutes to years) an emergency response (post-event).

5.2 Historical Context and Literature Review

Information acquired through graphical representations of infrastructure, sensing devices, and human reporting has been central to historical and contemporary fire protection. Within the broad purview of sensing for stationary structures, historical context along with the review of relevant literature are provided here to chart the path toward Smart Fire Fighting.

5.2.1 Context Through BIM

Building plans are an important element not only in fire protection system design but also in fire response. The detailed information provided in such plans are used to evaluate life safety and fire protection systems throughout the infrastructure life cycle. Even the simplest two-dimensional drawing can provide rich, contextually flexible information throughout the infrastructure life cycle (especially in the event of a fire). Recognizing the importance of representing the infrastructure in a graphical format, it is worth considering how modern drawing and design technology could be leveraged for Smart Fire Fighting. BIM, which is rapidly becoming the modern infrastructure design tool of choice, involves the generation and management of digital representations of physical and functional characteristics of structures. Currently, about half of the infrastructure stake holders in North America (including owners, design professionals, and construction companies) are using BIM, and that number could reach 75 percent by 2015 [2]. The value of this technology extends well beyond the design process and allows unprecedented management and integration functionality. BIM can represent diverse and comprehensive information dynamically and graphically, making it a powerful tool for data contextualization. With its ability to capture comprehensive information about the structure, BIM can be considered part of the sensing system for stationary structures due to its ability to provide spatial contextualization of sensors and people [3]. This basic contextual information can be used with a variety of higher-level models that assimilate sensor and BIM data. For example, research is being performed to deeply integrate BIM for automated design compliance (i.e., automatic code compliance check), automated building management technologies, code compliance, and fire fighter response [4].

5.2.2 Devices

Sensing devices have been used in fire detection for over a century. Smoke detectors (developed in the 1940s) alert occupants to fire, and automatic sprinklers (developed in the 1860s) sense and respond to fire and have resulted in dramatic reductions in property loss and fire casualties. For example, from 1977 to 2009, smoke alarm use in homes increased from 22 percent to 95 percent, while fire deaths and injuries reduced by more than 59 percent, in no small part due to those sensing devices [5]. The effectiveness of sprinklers has also been documented to show reductions in property fire losses by over 80 percent [6]. The impact of these widely adopted revolutionary fire protection devices is indisputable.

While the technologies have evolved over the years resulting in significant performance enhancements, the functionality of the devices remains focused on alarm and activation response functions. However, the convergence of innovations in sensing devices, network technology, and computing connectivity have advanced building management systems (BMS) toward true CPS frameworks with ever richer interactions between the physical and the virtual worlds. BMS used for energy management have charted the path for leveraging the pervasiveness, connectivity, and intelligence offered by emerging CPS technologies, which include (connectivity, intelligence, modality innovation, and pervasiveness) for sensors. Sensing devices are becoming smaller, cheaper with varied modalities, while connectivity is increasing. While centralized networking and monitoring functionalities are used extensively in the fire safety BMS, the networked fire and non-fire sensors could be exploited for fire safety information to support emergency response decisions. Much of the recent advancements in fire sensors have focused on multimode detection to avoid false alarms, adding new modalities to improve performance especially with regard to nuisance discrimination. Integration work has also been considered to leverage security cameras used for fire detection applications and occupant evacuation support. Additional research has been explored to evaluate performance of non-fire sensors in a smart fire framework.

5.2.3 People

The occupants of a structure and the general public provide an important means of sensing within stationary structures. Historically, "human sensors" provided the first distributed means of reporting the presence of fires and initial conditions of the response theater (structural layout, obstacles, locations of potential victim, etc.). In the very earliest iterations, the building occupants were relied upon to sense the presence of fire, then sound an alarm, operate a call station, or report directly to a fire station when a call for service was required. The advent of residential phone systems and eventually emergency call centers increased the speed with which reports could be provided and even allowed occupants trapped within a structure to access trained personnel to assist in their rescue (other than yelling out a of a window). In the past decade, personal communication devices, both in terms of health alert systems and now with the nearly omnipresent personal cellular phone, have greatly increased the ability of individuals to report hazards and request service from emergency responders at locations not tied to a specific stationary phone system [7], with demonstrated improvements in outcomes [8]. However, these approaches still rely critically on the five natural human senses to identify the presence of fire (or other emergency conditions) to initiate the call for fire service response.

The expansion of occupant-carried communication devices continues to thrive. The Cisco Visual Networking Index has projected that by the end of 2014 there will be as many mobile-connected devices as there are humans on the planet and that by 2018 there will exist 1.4 mobile devices per capita [9]. Highly portable and distributed computing and communications capabilities will be ubiquitous in our society. At the same time, the personal sensing capability of the modern smartphone, along with increased application development and distribution infrastructure available to the modern consumer, continue to increase the ability to sense and interact with the surrounding cyber, physical, and human infrastructure. Recent reviews on sensing capabilities of mobile phones have described the sensor-rich capabilities that these devices currently contain as well as a plethora of applications that have recently been developed.

As a result, the incident-reporting abilities of occupants and the general public may soon be more powerful and reliable. For example, Kamel Boulos et al. [10] describe how the Sahana Disaster Management System can use Open SMS to provide an opportunity for the general public to report emergency incidents with enhanced, locally sensed information compared to an ordinary phone call. Calls for emergency service are even feasible when the public is unable to make the call themselves. For instance, Sendra et al. [11] provide a framework for using smartphone-based sensors within a population of individuals to automatically determine if an emergency has occurred and automatically notify emergency services, specifically with applications in the elderly population.

Mobile sensors carried by the general public may also assist emergency responders in locating victims and assisting them in locating a safe haven or egress from the structure. The ability to identify mobile devices has been proposed as a method to estimate numbers of victims who may be in a tunnel during fire incidents. Dekdouk [12] presents an emergency response management service assisted by sensors on distributed mobile tablets along with those integrated with building sensors to compute estimated victim location and the safest route to locate them. Nakamura et al. [13] present an evacuation support system to assist self-evacuation based on information collected by smartphones and tablets (mobile terminals). Roggen et al. [14] describe the use of mobile sensors for understanding crowd dynamics that can be extended to improving emergency situational awareness of the crowd.

These are just a few examples of how occupant-carried mobile sensors may soon provide fire fighters with powerful information about and the ability to interact with the people whom they are sworn to protect As the computing and sensing power of smart mobile devices pervades our society, the ability for occupants and the general public to identify, report, and even potentially begin to mitigate an emergency will continue to expand. The technology-enabled “initial responder” can play a key role within the stationary sensor environment to enhance smart fire fighters’ response capabilities with immediate, local information.

5.3 Summary of Current State of the Art

Information technology has transformed the way that information is acquired and utilized, potentially adding tremendous value in the support of critical decision making. This information is gathered in situations as varied as calorie counting to police dispatching. The current state of the art in information acquisition is provided to assess the ability of current BIM, devices, and people to support critical decision making in fire events and to identify opportunities for advancement. This status is provided in terms of their application to essential functions, performance in basic metrics, and functionality in areas known to be important for true utility. These considerations will reflect the ability of current information acquisition technology to support current fire fighting decision-making and, ultimately, for current and emerging technology to be widely adopted.

5.3.1 Applications

In a virtually endless set of situations, stationary sensors are installed to acquire targeted state information on the (1) infrastructure, (2) environment, and/or (3) occupants for situational awareness and response. These sensors use acquired information for a myriad of non-fire infrastructure management (e.g., comfort, security, and energy management) and fire safety functions. Current BIM, sensing device, and human sensing technologies are just beginning to unlock the opportunities created by the connection of sensors, computers, infrastructure, and humans (i.e., cyberphysical systems).

Currently BIM is used to support the design and construction of mechanical systems. The visual representation of construction geometry is useful for documenting building elements and identifying design and construction inconsistencies. BIM databases serve as a rich source of information for other design and performance purposes beyond installation and construction; however, mining information can be challenging due to compatibility issues with functional design and analysis software and BIM software. These compatibility issues limit utility. In fact, the design of software required to extract information can become prohibitively challenging, making redesign or re-entry of database information an attractive option and removing the utility of BIM for functional design and analysis. Sorting out the compatibility issue will be important to make use of the information in BIM for fire interests.

The benefits of devices focused on our comfort, security, and safety (e.g., fire safety) are well understood and documented. Recent advances in sensors, computing, and connectivity provide new opportunities for higher levels of building automation. Ever increasing energy costs have made the energy management use case for connected smart sensors increasingly compelling while raising awareness of the strong value propositions presented by these devices. The explosion of the Internet of Things (IoT) has opened imaginations to all kinds of applications for connected smart sensors. Self-driving automobiles, bio-connected wearables, and ultra-efficient green buildings are quickly becoming a reality. These emerging applications should point the path forward to inspire Smart Fire Fighting. The personal computing power of the modern smartphone and the increasing cyber-physical infrastructure available to the modern consumer has increased applications that an individual can carry. Apps are available to help roughly locate individuals or identify specific health/physical concerns or limitations. Distributed personal phone systems allow occupants to communicate with other potentially trapped victims. The widespread distribution and acceptance in the general public are ongoing.

In addition to applications during emergency response, the pictures and videos that can be rapidly collected in a distributed manner on mobile platforms can be aggregated by willing participants to provide critical evidence in forensic analysis. Such a crowdsourcing approach would be analogous to the collaborative driver assistance services that can provide traffic condition monitoring and advisories from distributed mobile cameras in vehicles.

5.3.2 Performance

The performance of the information acquisition system is characterized in broad areas described by (1) the value of the information acquired; (2) the speed at which the information can be delivered; (3) the trustworthiness of the information; and (4) the cost of acquiring the information. It should be mentioned that while connectivity is not treated as a principal performance metric in this discussion, it is an important factor that strongly impacts the performance. This characteristic affects the performance so pervasively and profoundly that it is addressed exclusively in the functionality section.

BIMs currently provide valuable physical information, which can include dimensions, physical properties, and functional properties. The apparent value of this information has been realized in design and construction. However, the latent value of BIM data is only now being recognized. As a first step in increasing the utility of BIM data, geometry information is often imported into functional performance simulation and analysis programs including those used for fire analysis (e.g., the Fire Dynamics Simulator). The digital format of BIM information facilitates fast delivery. The Internet, database integration, and pervasive connectivity through cellular and WiFi networks further increase the potential for fast real-time data availability. GPS-based navigation software provides a poignant example of how geometry-based software can be integrated with sensors to provide real-time location information. It is easy to imagine how BIM software could be integrated with emerging indoor mapping and positioning technology for real-time indoor navigation. BIM information might be extremely accurate near the time of construction; however, the built environment can be very dynamic and the trustworthiness of the information can be questionable without frequent BIM database maintenance. The cost of this maintenance needs to be considered in the value proposition of BIM integration for fire sensing.

There is an abundance of modality options available for sensors depending on the measured quantity of interest. The value of the information measured is more a function of the synthesis of the measured data than the modality of the measurement. Careful decisions regarding the number, location, modalities, and algorithms are thus key to increase the value of sensor data. Smoke detectors provide excellent examples of how modality synthesis can enhance device performance. Multi-critera detectors rely on multiple modalities (e.g., photoelectric, heat, carbon monoxide) to improve response times and reject false alarms from nuisance sources. Increasing power and connectivity of computer resources including embedded computing provides opportunities for elaborate algorithms and even models to further improve performance increase value of information. The accuracy of sensors is adequate for current applications, especially in fire, where the expectation is simply to alarm. However, as expectations rise to provide higher value information requiring more sophisticated synthesis, ensuring sensor trustworthiness will become more challenging. This trustworthiness is central to the value of the information. Novel semi-conductor based sensors are driving the cost of devices down while increasing their installation density. The increase use of long-life battery power and wireless capabilities further reduces installation costs. These same factors might also impact sensor trustworthiness.

The quality and quantity of the information that the fire service can glean from occupants and the general public depend largely on the abilities of the human operators. While modern cell phones allow much more distributed and personal sharing of information than do street-based fire alarm call boxes of the past, these tools are still limited by human factors. Information provided to emergency call centers is strongly dependent on the ability of the caller to verbally translate conditions to an operator. The training of the human operator is equally critical to gathering the appropriate information while providing a platform for collaboration with the caller. Modern communication technologies utilized by the general public are typically dependent on a relatively open cellular or wireless infrastructure. While the infrastructures are improving in reliability and coverage at a rapid rate in most locations, their ability to be hardened to guarantee reliability and performance during an emergency remains a concern. Additionally, multi-story structures often have areas of refuge where mobility-impaired occupants can report to await rescue and communicate with responders. Currently, the tools that are available are largely "come find me" apps that must be physically initiated by the occupant and provide the general location.

5.3.3 Functionality

While the four performance metrics previously discussed will affect the functionality of the information acquisition system, connectivity deserves discussion as a special consideration for its impact on how well the information acquisition systems is able to perform its intended purpose. While basic applications required from stationary information acquisition systems remain unchanged, advancements in their connectivity continue to revolutionize the functionality of these systems. The current status of (1) sensor-computer connections, (2) sensor-sensor connections, and (3) sensor-human connections is addressed in the context of information acquisition system functionality.

The current BIM interface relies on human connections. These models are created by users through computer, software, and drawing input devices. It is apparent that the software will play an important role in the functionality of BIM, and there is always room for innovation. However, BIM functionality is largely static, and there are opportunities to move this technology to interface not only with people but also with sensors, creating dynamic experiences to accelerate information flow through automated input, real-time, and/or super real-time observations. Sensor connections with computers provide higher level of automation, and sensor connections with other sensors provide opportunities for higher levels of discernment (e.g., false alarm rejection with multi-criteria smoke detectors) when used with embedded or even external computing technology. These sensors are often also connected to automatically contact monitoring services, thus including multi-sensor–computer–human connections. There are even greater opportunities to integrate the disparate building system sensors with each other along with BIM visualization technology to provide even richer information to support critical decision-making.

Modern personal communication devices, such as cellular phones, provide an incredible platform with functionality that is just scratching the surface. Traditional fixed telephone systems only provided the ability for voice communications with call centers from a relatively stationary location. Smartphones can provide streaming video and sharing of pictures to enhance the voice communication. Modern smartphones also contain a suite of sensors that can determine a person's orientation or motion, which can be used as an estimate of their location or movement patterns. However, the information from these phones is useful in the emergency response only if it can be accessed and interpreted by responders and if the occupant is actually using the phone. Additionally, there has been an influx in the interaction between building systems and cellular phones, particularly when dealing with security, lighting, and comfort controls within a building. In some cases, the building elements can collaborate with the human operators on their cell phones to make decisions ("Did you mean to leave your garage door open for the past 10 minutes?"). In addition to the advancement of smartphone systems, simpler systems, such as a one-way call for help button, are often carried by individuals at high risk for requiring aid in order to indicate an emergency. These systems often have limited bandwidth and communications capability ("Help me, I have fallen").

5.4 Summary of Perceived Future Trends

5.4.1 BIM and Devices

As BIM becomes more widely adopted for design and documentation of building construction for fire and non-fire applications, there will be increased opportunities to leverage this technology to inform fire safety decisions during (or even in advance of) a potential fire event. Emerging indoor mapping technology (used for wayfinding and retail) will only increase available BIM information for existing infrastructure and facilitate its use for safety applications. BIM has also inspired the exploration of the feasibility of automated code compliance through ICC's SMARTcode initiative. Recent studies in the fire community have focused on the use for BIM in determining building fuel load and the real-time integration of sensors and BIM to support critical fire fighter decisions. The data from BIM models could be integrated with emerging connected municipal database containing inspection data and other relevant building data. These databases are proving valuable resources for data analytics initiatives such as FireCast developed by FDNY for risk management. FireCast uses algorithms and database information to assess the relative fire risk of all buildings within the city, creating a daily risk map for resource management and prioritization.

New multi-modal semi-conductor based modalities having wireless communication and location awareness capability are emerging for environmental monitoring in buildings, including fire applications. The pervasive use of cameras for security within buildings should also be mentioned. Aggregating and integrating this disparate sensor data on a common building information management system is already happening. However, the dramatic increase in sensor count is creating new challenges for managing the information acquired by these sensors. The computing and analysis infrastructure does not yet exist to synthesize data from the various building systems (collected on this common data network). This synthesis is critical for the delivery of high value information to support emergency decision-making. The new material, power source, and low power computing technologies used in these devices is driving down capital, operating, and maintenance costs, which is resulting in dramatically increased sensor density in these buildings. As the cost of these sensors continues to drop, disposable sensor technology may even become viable. The battery life spans of some of these sensors can approach 10 years. With these factors in mind, it is easy to imagine that these sensors could be replaced at the end of their battery lives, like light bulbs.

5.4.2 People

Future applications in occupant and general public sensing in support of emergency response will build off personal, portable computing platforms that promise to become more powerful while also smaller and more transportable. Although it is impossible to predict the future of this rapidly changing field, several advanced applications appear poised for success in the near future. For example, the ability to truly collaborate with installed building systems — fire as well as security, HVAC, and so forth — could allow for the development of collaborative apps that guide a trapped occupant to safety through navigation of unknown hallways and underutilized escape routes as well as allow occupants to collaborate with and potentially assist others. Personal health systems may be able to automatically begin basic medical assessments and communicate the data to responders as opposed to simply indicating that assistance is needed. Applications to improve the interior locating of occupants (within less than 0.1 m) as well as assess health status and viability of those occupants will enhance command decision-making capabilities.

Performance of occupant-carried sensors will be improved by the increased ability to collaborate with both human and physical infrastructure. In transitioning personal applications from "come find me" to "help me evacuate" functionality, robust two-way voice and data communications must be present, location capabilities should to be hardened to within ~10 cm, and the system can be reliably activated by an event or emergency responder without requiring occupant initiation. Call-in information from trapped occupants can be automatically enhanced with video and data from local sensors to improve the timeliness and accuracy of decisions required of company and command officers well before they arrive on-scene. Areas of refuge could be replaced with areas of self-assisted egress. As the cost of computation resources continues to decline, the ability to embed local computation and decision support will greatly improve the efficiency and speed of these communications and fire service decision support capabilities.

Additional measurement modalities may also be leveraged with future occupant sensor suites. Local measurements of key ambient quantities such as temperature, humidity, air quality, or possibly even specific gas species are possible on smartphone platforms. Smartphones could also reliably and seamlessly collaborate with non-human-based sensors installed within a structure in a trustworthy fashion to improve the quality of local sensor measurements and distributed computations. Body-worn personal monitoring sensors (e.g., FitBit) are becoming more accepted by the public as a whole. Continued development and integration into an emergency response occupant location/status system will improve situational awareness for responders. As these systems continue to be miniaturized, their functionality and form factor will become more seamless, which will eventually transition to noncontacting and implantable devices.

5.5 Technology Gaps, Outputs, and Outcomes in Support of Research

5.5.1 BIM and Devices

The efficacy of information acquisition and delivery through BIM and sensor integration depends largely on seamless interoperability, system trustworthiness, and meaningful workflow integration. These important attributes indicate gap areas in CPS-based information acquisition technology. Interoperability challenges prevent sensors not necessarily from sharing common networks, but from sharing common algorithms or computer models. This disconnect prevents deep synthesis of information limiting the value (or quality) of information for decision support. Currently there is an interoperability gap related to the ability of data analytics to integrate data from a disparate sensing sources, including BIM, to curate and enhance the information provided to decision makers. With the increasing quantity, variety, and speed of information, there are real challenges in obtaining seamless interoperability. These issues—along with BIM accuracy, sensory accuracy, sensor reliability (associated with battery power limitations), and information security—will also impact trustworthiness. It is not yet clear how this emerging information acquisition technology will be used in fire fighter workflow. There is a need for fire fighters to be engaged in the exploration of the capabilities of this emerging technology to understand how to best integrate it for real-world use. All too often, CPS systems are developed by information technology experts without end-user input. However, fire fighter engagement is critical for widespread adoption and impact of this emerging technology on decision-making in fire emergencies.

5.5.2 People

The potential applications for utilizing the mobile computing platforms are limited largely by the creativity of the developers of apps and the support of communications protocols that allow reliable, trusted collaboration among all information sources at an emergency scene. Unlike the other sensor systems of interest in this roadmap (see Chapters 3 and 4), many of the devices in stationary sensor systems are developed for applications other than emergency response or are of personal purview. Thus, to leverage these sensors in order to expand applications, protocols for trusted interface between the building systems and personal smartphones are necessary. To increase the quantity and improve the quality of applications for occupants sensing capabilities, the human sensors themselves will have to be trained to understand what they can (and should) be sensing, recording, or reporting. Such public service training is an important aspect of early detection (e.g., "See something, say something"), but as the technology available to the general public increases in complexity, so too will the messages and the training required.

Among the critical performance enhancements needed for these distributed sensing systems to be in operation for the general public's use during an emergency, improvements are needed in durability, human factors interface, computing power, and the handling of privacy concerns. The environment in an emergency likely will have some combination of clutter and visual impairments (dark or smoky), with dynamic physical contacts possible. In order for the occupant and the fire service to trust the sensors, they must be durable enough to survive this physical environment while also providing protection from cyber-based attack and vulnerabilities. The interface must be easy to read, understand, and interact with and follow a common, standardized platform and protocol to ease training requirements. Additional local computing power, either on the personal device or within local installed systems that the personal device collaborates with, will increase the efficiency with which decisions can be made. All these performance metrics should be achieved with minimal (if any) realized cost to the occupant in order to achieve widespread acceptance and utilization.

Functionality of sensor systems for the general public likely will be controlled by the economics of the sensing modalities available. Development of cheap, small, yet robust sensors that can be incorporated into personal computing platforms will improve the likelihood of their inclusion on a common platform. At the same time, it must be acknowledged that the driving factor behind inclusion of these sensors likely will be some application other than emergency response due to the commonly held belief that such a disaster is not likely to happen. For example, cellular phones combined with social media infrastructure are designed to network with peers on a private platform. Providing a functionality that will support streaming of video or sharing of pictures that may be useful in locating an individual or beginning treatment of medical emergencies will require public access to private information. To support these increases in functionality, trusted data-sharing protocols are a must. At the same time, open architecture that allows interfacing with building sensors and devices might be seen as a vulnerability to building managers and must be protected.

5.6 Perceived Priorities for Research

Even now, the adoption and evolution of CPS are happening all around us. However, there is a need for research, technology, and system development for implementing and advancing this technology for fire emergency situations.

5.6.1 Research Priority Summary

The integration of BIM and devices for real-time virtualization represents an unprecedented opportunity to improve fire fighter safety and operational efficacy. It is critical for the fire research community to engage and provide leadership to the Internet of Things (IoT) industry to ensure that the inevitable CPS safety systems that will be developed can provide real value to fire fighters. While IT, computer, and sensor technology are essential to fire focused CPS, there is a research need in understanding how best to acquire, synthesize, and visualize information to support fire fighters using available IoT technology. This technology needs to be careful curated and developed for use in fire applications. Research is needed to determine how existing buildings sensors, BIM, and emerging sensors can be synthesized to support fire fighter decisions. This research would involve test beds focused on critical information acquisition performance issues related to providing high value information. For example, a data synthesis focus would explore optimal modalities, locations, number of sensors, and information synthesis approaches to provide timely actionable information to fire fighters without overwhelming them with data. Alternatively, a trustworthiness focus would focus on minimizing the uncertainty of the information provided by BIM and sensors and developing fire fighter trust in the CPS. While performing research to deliver high value information is essential to develop next generation fire information acquisition systems, it is also critical to explore how to best present this synthesized information to decision makers for seamless workflow integration. A visualization and information delivery test bed would be useful to explore how decision makers can effectively interact with the CPS to support fire fighter operations.

The most critical priority for general public fire sensor system advancements lies in the ability to synchronize these capabilities seamlessly with people's daily lives. Research must be conducted to integrate requisite sensors and communications capabilities into common hand-held computing environments that occupants will carry with them at all times. Thus, miniaturization and mass production of critical thermal or gas sensors into these tools will allow them to be distributed more broadly. At the same time, critical research in trusted, secure, yet accessible communications protocols must be developed to ensure that privacy concerns of users and security concerns of the fire service are considered. The ability to synthesize the massive data streams that are carried and maintained by the public into a decision support tool for the fire service will require protocols for determining the trustworthiness of the incoming information (based on quantity, quality, consistency, accuracy, and so forth) and human factors study of the appropriate amount of information to share with incident commanders based on the determined trust level. In some cases, these solutions may be generated by leveraging various different communities, ranging from traditional academic research in mobile computing to informal gatherings at "hackathons."

The most significant barriers to success in this realm include public privacy and cost concerns. Anecdotally, the general public is often reticent to pay a premium for fire protection infrastructure, hence the necessity either to leverage technologies developed for other applications or to drive the costs down for specialized technology. Civil liberties and safety are often at odds in our society, so the ability to achieve the broad public-private partnership required to leverage general public fire sensor systems requires addressing concerns over privacy, policy, and trustworthiness.

5.6.2 Proposed Smart Network Infrastructure for Fire Resilience (SNIFFR) Engineering Research Center (ERC) Case Study

A case study highlighting a proposed research and development plan to realize the smart sensor vision is presented as a case study. The research vision was developed by a team of researchers assembled by Prof. André Marshall (University of Maryland, College Park), Prof. Jay Gore (Purdue University), Prof. D.K. Ezekoye (Univ. of Texas, Austin), and Prof. Gilbert Rochon (Tuskegee University). The proposed comprehensive engineering research plan builds on networked sensors concepts introduced in this chapter.

5.6.2.1 Summary

America's investment in infrastructure is ever vulnerable to fire and natural disaster. Even in natural disasters, it is often the ensuing fire that leads to human tragedy. The total cost of fire in the U.S. has been estimated to be as high as $350 billion, or 2.5% of the U.S. gross domestic product (including monetary equivalents for deaths and injuries). Hotter and drier weather, shifting rain patterns, and deeper mines and wells all contribute to the persistence of these threats. Historically, technological advancements have helped to manage the threat of fire and reduce loss. However, despite continuous advancements in fire technology, the challenge to eliminate catastrophic fires is still daunting. There is a real need to innovate beyond the paradigms of century-old technologies (e.g., smoke detectors and automatic sprinklers). Fires are pervasive, yet rare and uncertain. The unforeseeable nature of fire necessitates timely sensing and information for effective mitigation (prevention or response). The proposed Engineering Research Center (ERC) Smart Network Infrastructure for Fire Resilience (SNIFFR) seeks to eliminate fire disasters in 21st century society through converging innovations in broadband sensors, dense sensor networks, numerical modeling, ubiquitous distributed computing, and active human-in-the-loop communication networks. The SNIFFR will be perceptive to determine the state of an incipient or developing fire or even to sense conditions that may lead to a fire. It will utilize available robust sensors for vigilance over time, possess durability in a fire, and maintain cyber-security. The SNIFFR will be smart to synthesize the sensor data into a coherent incident state, fast to provide timely state information for fire response (or prevention), and clear to communicate high value information (i.e., meaning) for critical decision making.

The proposed SNIFFR ERC focuses on the integration of fire-related perception (e.g., high-density distributed sensor networks) and communication (e.g., broadband wireless systems) through next-generation analytics (e.g., super-real-time data-driven models) to deliver high-value information (via advice or inquiry). The SNIFFR technologies would transform signals generated in fire resilience systems from "communicating alarm" to "communicating information." These analytics greatly enhance the value of the sensed signals and the corresponding response. The analytics required to transform fire-related perception into meaning do not yet exist. A database of sensors and their response to peculiar smells, sounds, sight, heat, and light (radiation) of typical fires and their standard response is needed for customized ubiquitous sensing. Robust networks and protocols are required to deliver the sensor data to computing resources for processing. Fast computer models are needed to synthesize the sensor data for fire assessment (including fire development and human behavior). System hardware and software developments are required to effectively communicate this rich fire assessment information to the people who need it. A method to quantify and manage the propagation of uncertainty as information flows from perception to meaning is critical to ensure information delivery in the context of confidence. The development and integration activities proposed for the SNIFFR ERC would provide a transformational framework for model-enabled fire resilience systems capable of communicating meaningful information for decision making (e.g., recipient specific and/or prognostic information) in fire incidents and other emergencies.

The proposed SNIFFR ERC would bridge the fire safety technology gap, providing U.S. communities and infrastructure with the innovative safety technology expected of an engineered system with such expansive reach and profound consequence (personal and commercial). These new technologies would disrupt the status quo by adding unprecedented value to support a much-needed science-based innovation ecosystem in the fire safety industry. The proposed multidisciplinary, integrated research activities extend and anchor the fire safety engineering discipline beyond the thermal sciences through new inter-departmental and inter-university research connections in sensors, networks, big-data, fire physics, social sciences, and communication theory, equipping a new generation of researchers and engineers with deep and diverse skills for contributions to industry.

5.6.2.2 Ten-Year Vision

Fires are a global problem that have profound social and economic consequences. In 2010, the total cost of fire was estimated to be approximately $350 billion or 2.5% of the U.S. gross domestic product, which includes economic loss, fire department costs, and monetary equivalents for deaths and injuries. Ultimately, the proposed Engineering Research Center (ERC) Smart Network Infrastructure for Fire Resilience (SNIFFR) seeks to eliminate fire disasters in the 21st century. The ERC purposes to accomplish this bold vision through SNIFFR technology, enabled by fire, communications, and network sciences, which will communicate high-value information to guide critical decisions made by occupants, first responders, and other subsystems.

This vision aligns with and complements major initiatives of our stakeholders (e.g., government labs, the sensor and control industry, as well as the insurance sector) especially when considering the distinct focus of the ERC program on innovation, workforce development, near-term technology, and long-term fundamental research. In the next ten years, the SNIFFR will accomplish the following:

- Transform fire sensing and communication systems into smart decision-guiding SNIFFR systems by performing seminal work in the development and integration of innovative models into these systems
- Demonstrate the ability of the SNIFFR system to mitigate fire disaster (through prevention or response) in test beds addressing globally important fire issues to drive technology toward adoption
- Catalyze this technology-lagging industrial area by establishing a self-sustaining SNIFFR innovation ecosystem with Fortune 100 sensor and control companies, entrepreneurial small businesses, federally funded R&D centers, government labs, government agencies, owners, underwriters, regulators, system designers, and builders of urban interfaces, buildings, and transportation systems (all of which have long-standing connections with the University of Maryland Fire Protection Engineering Department and its partners)
- Infuse stakeholder institutions with SNIFFR graduates and students enlightened by fire-focused perspectives and possessing the deep multidisciplinary skill sets required for the development of revolutionary fire safety technologies.

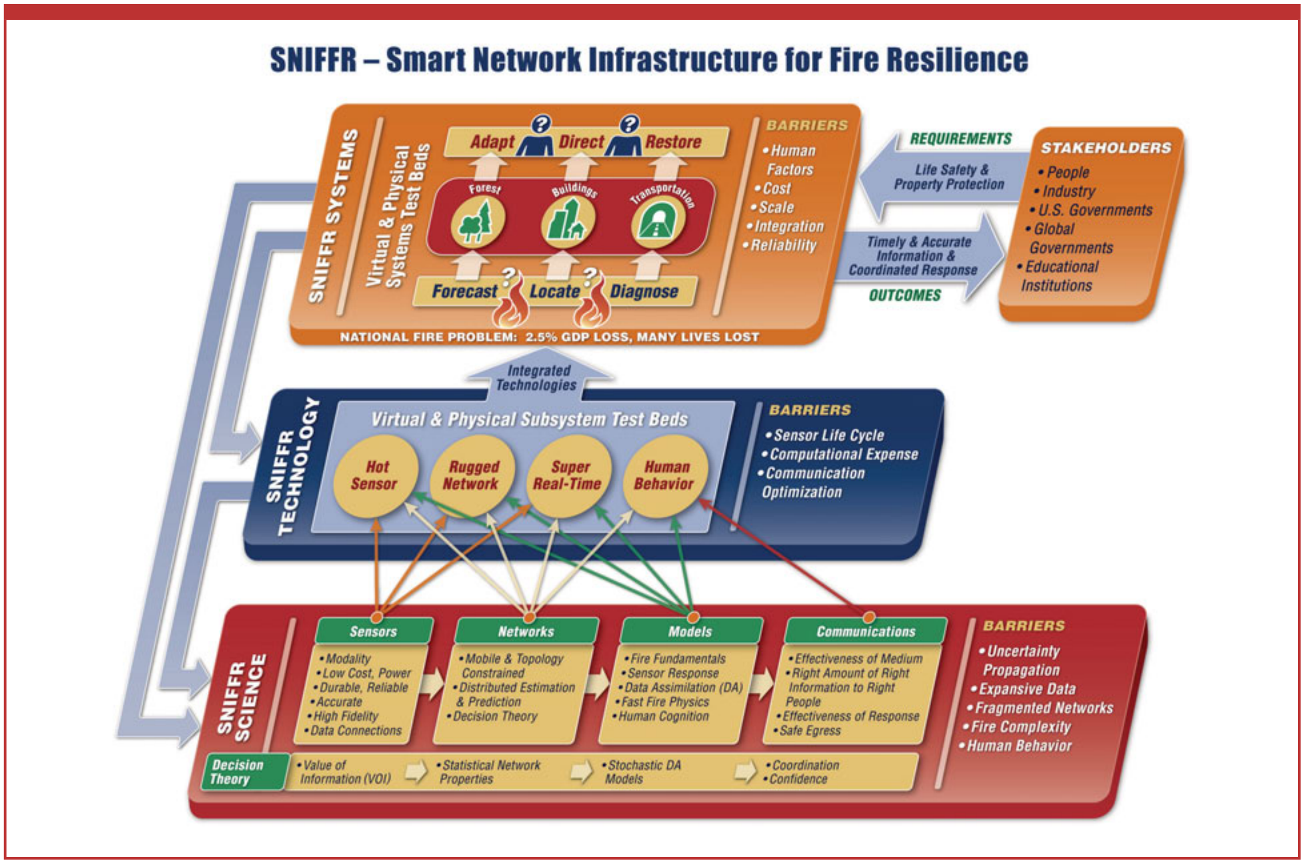
The team will extract the compelling value offered by the ERC framework in order to realize the SNIFFR vision. The strong external interdependence between the fire, physical infrastructure, people, and the SNIFFR system, and the equally strong internal interdependence of SNIFFR subsystems, requires system level guidance from subsystem technology test beds and subsystem level guidance from research thrust areas. Further, the broad stakeholder involvement in the ERC is crucial to develop consistent protocols for SNIFFR adoption.

5.6.2.3 Research Strategy

The proposed ERC SNIFFR is described in the 3-plane chart (Figure 5.1). SNIFFR is focused on developing a broadly applicable engineering system to sense, acquire, decipher, and communicate timely and accurate information for critical decisions in incipient and developing fire emergencies to save lives and protect property (see Stakeholder Requirements and Outcomes in the 3-plane chart). The SNIFFR system framework will be valuable in a range of populated fire emergency scenarios of national importance, which include the wildland urban interface (WUI), buildings, and transportation networks as shown in the system plane of the 3-plane chart. In the proposed ERC effort, the SNIFFR system will be evaluated in test beds provided by stakeholders in the corresponding sectors of the infrastructure economy. Subsystem level evaluation of technologies integrating the thrust sensors, networks, models, communications, and decision theory underlying all five are needed, as shown in the bottom plane of the 3-plane chart.

New insights are needed to move from the “alarm” to “information” paradigm of the SNIFFR system. Collectively, these insights will enable the SNIFFR system performance, and it is particularly in the context of these insights that the thrust activities (discussed in more detail in 5.6.2.4) achieve focus. To sense and acquire the information about incipient or developing fires, the Sensors, Networks, and Decision Theory thrusts and Hot Sensor and Rugged Network test beds will enable the development of (1) new and repurposed multi-functional sensors that provide benchmark measurements for model validation and in-field performance; (2) a comprehensive database for the quantitative response of various sensors to a fire (according to fire properties and sensor location); (3) communication protocols/software enabling sensor information transfer

Figure 5.1 3-plane chart for Smart Network Infrastructure for Fire Resilience (SNIFFR).



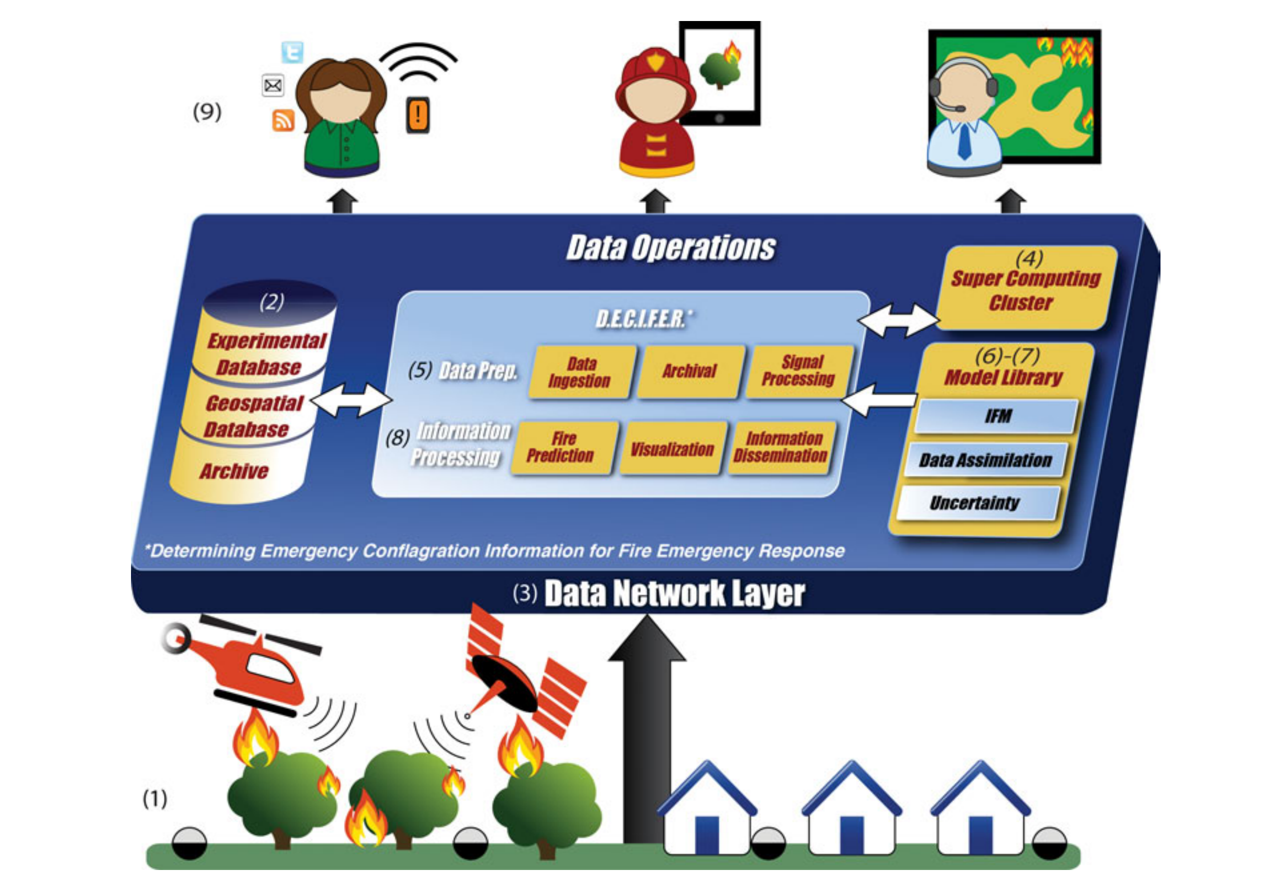
to data processing computers; and (4) optimal architectural layout of processing computers given constraints imposed by fire size and location. In order to decipher the information acquired from the sensor networks, the Model and Decision Theory thrusts and Super-Real-Time test bed will enable development of (5) computer models that interpret the sensor signals and convert them for use in predictive tools; (6) computer inverse models identifying the real-time fire state and super real-time forecasts; and (7) framework for uncertainty estimates inherent in data and predictions in sensor and computer models. Ultimately, deciphered information must be delivered to people or response subsystems. To this end, the Communications and Decision thrusts and Human Behavior test bed will enable development of (8) protocols/software to extract only necessary information for guidance; and (9) communication protocols/software to transmit and display critical information.

The resulting SNIFFR system, outlined in Figure 5.2, could prevent an incipient fire, and in the case of a developing fire, assist in fire fighting efforts by forecasting and providing safe egress routes and available time to occupants. The fire-shielded sensors will wirelessly communicate the measurements to a central processing unit, where they will drive the real-time analysis to forecast the future condition of the fire, structure, and tenability. This forecast, along with critical decision-making information, will be communicated back to the occupants and fire fighters in "super-real-time." This forecast will be dynamically updated as new sensor data become available.

5.6.2.4 Fundamental Research Plan

Sensors Fire sensors and repurposed fire sensors can be classified as thermal (temperature and heat flux), chemical (CO, hydrocarbons, gases, O_2%, photoelectric or ionization smoke detectors), optical (visible or infrared mounted in buildings or unmanned aerial systems), and structural (stain gauges, deflection cameras, and plumb bobs) [1–9]. All of these sensors provide useful but different information about the fire environment and have different cost, power, and data processing requirements. Optical techniques are limited to the field of view and thermal and chemical sensors depend on the gas flow.

Figure 5.2 SNIFFR system framework applied to WUI. Items 1–9 highlight enabling insights described in 5.6.2.3.



Thus different types of sensors are required to "sniff" a fire. Further, the fire sensors must often be wireless, networked [10, 11], and fire-hardened [12, 13]. If a fire starts, an effective sensor network must continuously (1) monitor the environmental conditions, (2) identify and track occupants and fire fighters, and (3) determine the state of the infrastructure under fire insult (e.g., building, transportation), and (4) monitor the interdependent health of the environment, people, and structures. The raw data from sensors also need to give a spatial and temporal context before forwarding for analysis. Data-driven predictive fire sub-models provide an example of this approach.

Based on SNIFFR system requirements, it is apparent that a large numbers of sensors would positively impact the uncertainty propagation barrier for accurate information; yet vast quantities of data are inherent to this approach, creating the expansive data barrier for timely information. The cost of continuously monitoring all the sensors all the time will be addressed by developing smart sensing methodologies, which could involve some of the low or zero power sensors along with the environmental sensors like temperature and humidity in the safe-state, and by activating the rest of the sensors if a fire-state develops. Decision theory will be applied using value of information (VOI) models to determine where and which sensor inputs have the most impact.

Networks Sensors, network management centers, and base stations that are located both on site and in hardware and software of the underlying Wireless Sensor Network (WSN) will be jointly designed to guarantee power-optimal performance [14,15] of the mobile nodes and resiliency of the overall network [16]. Distributed detection and estimation systems will address the fragmented network and uncertainty propagation barriers, enabling accurate and swift fire detection, while also resolving information for safe evacuation and fire fighting. The fusion of measurements collected by sensors that are of different types and placed at distinct locations will be accomplished using a model-based approach [17] that encapsulates the underlying physics of fire growth and propagation via distributed filtering algorithms that are scalable and dependable in the presence of intermittent [18] and fragmented networks [19, 20]. The implementation of these functionalities will follow the Keppler workflow system [21] of real-time data processing. Decision theory activities applied to the networks include characterizing the statistical properties of the WSN for incorporation into the workflow system.

Models Computer-based models have been applied to fire protection engineering problems and have emerged over the past three decades as powerful tools for basic understanding, system design, and forensic analysis. Models are routinely applied to simulate fire spread and smoke transport; the evacuation of building occupants in response to a fire; and the structural resilience of buildings to fire loads. Current fire models are limited in scope because of the large uncertainties associated with both the accuracy of physical models and uncertainties in many of the input parameters to the fire problem. A promising approach to overcome the limitations found in numerical simulations of fires is data assimilation (DA). DA consists of integrating computer-based fire modeling with sensor technology [22–32]. DA provides an optimized approach to overcome the barriers associated with fire complexity and human behavior barriers (i.e., complex multi-physics systems influenced by a large number of unknown or partially-known input parameters). While still original in the field of fire, DA is an established approach in several scientific areas such as numerical weather predictions. The idea of data assimilation has been explored recently by several fire research groups, both for wildland and for building fire applications. Data-driven fast physics fire models will be developed and evaluated to (1) forecast fire spread and fire plume dynamics (Forest test bed); (2) detect incipient fires, optimize the response to a growing fire in terms of providing safe egress, assisting first responders, activating building systems, for example, fire suppression systems and HVAC systems (Building and Transportation test beds); and (3) monitor the health of a structure and/or an engineering system (Building and Transportation test beds) supported by fire fundamental experiments. To support the use of these models for decision making, parameter inference tools will be used to produce stochastic models to assimilate the sensor data. Compact mathematical representations to model under-sampled probability distributions and computationally efficient models for uncertainty propagation will be developed.

Communications The effectiveness of fire warnings transmitted to occupants is an important area of research, as people do not respond well to non-voice signals (e.g., alarms, sirens, and bells). Further, decisions about evacuating from fire-focused warnings may involve delays due to searches for additional information [32]. Brennan [33] underscored that fire fatalities tend to include a disproportionate number of elderly and disabled, that is, high-risk demographic groups in society. To address the human behavior barrier, the proposed research program will use experimental settings along with field tests of our sensor communications technologies at the Maryland Fire and Rescue Institute (MFRI) or Purdue's Homeland Security Institute (HIS) to understand the best way to communicate information, not just alarm, to residents across a spectrum of ages and abilities. Collaboration will add value to the occupant focused communications and incident commander focused decision theory thrusts.

Decision Theory Decision theory will be applied to develop a framework that (1) identifies the information used by decision makers (DMs) in the system test bed environments, (2) characterizes the sources and properties of uncertainty in sensor-data, models, and networks, and (3) communicates information relevant to the alternative strategies that a DM is considering [34]. The decision theory approach directly addresses the human behavior barrier while guiding overall SNIFFR development. The focus will be on DM incident commanders (ICs) engaged in fighting forest, building, or transportation fires. These ICs are responsible for deploying resources to mitigate the fire and evacuating civilians from the fire threat. Research on naturalistic decision making (NDM) and decision analysis will be used, considering decision processes under stress and use of sensor data and other information to increase situation awareness and inform options analysis [35–36]. Expert incident commanders from the three test bed environments will be surveyed to encapsulate their information gathering, assessment, and decision-making strategies into mathematical models, through which the type of information that most affects their decisions can be identified along with the sensitivity of decisions to this information. In the SNIFFR system, sensors, sensor networks, models, and communication networks provide information to increase situation awareness. Since sensor signals do not perfectly map to the state of the environment, there is noise in networked signals, and models contain bias and model parameter uncertainty, one can consider that the nominal outputs are enveloped in uncertainty. To address this, the overarching objective of the decision theory thrust is to best synthesize the data, network characteristics, and models to reliably communicate the system state given the state of uncertainty across all planes. The decision theory has been integrated throughout the thrust area and test bed discussions.

5.6.2.5 Technology Development

Hot Sensor The SNIFFR sensors will be exposed to laboratory controlled conditions simulating fire sources (e.g., combustion gases, soot particles, flame emission) and nuisance sources (e.g., steam, ambient light) to determine sensor response (i.e., what the sensor "sees") with a focus on discrimination between true fire and nuisance signatures. This test bed will explore detector innovations, imaging innovations, and Unmanned Aerial Systems innovations. Critical items such as network continuity, degradation of sensor performance, and ultimately sensor failure will be monitored and can serve as additional key data points for the SNIFFR. The observed fire conditions will be simulated and sensor responses will be correlated with those of a sensor model for calibration and improvement of the latter.

Rugged Network Accurate and reliable processing of sensor data must be provided (sometimes under extremely tight energy consumption constraints, depending on the application) for the rugged sensor networking required for the SNIFFR. Signal processing design methodologies and digital subsystem architectures for system-on-chip integration will be explored using the variety of sensors employed in the rugged network test beds. Critical challenges in jointly providing ultra-low power operation, secure wireless communication, accurate sensor signal processing, and efficient integration with heterogeneous sensing devices will be addressed. Extensive previous work by the investigators in developing energy efficient application-specific integrated circuits and signal processing techniques for surveillance-oriented sensor networks [14, 38] provide a solid foundation for these efforts. Decision theory efforts will focus on developing VOI models to determine which networks are most important and require the highest reliability and redundancy.

Super-Real-Time Prototype software cyber-infrastructure will be developed for this test bed that integrates data-driven estimation and prediction models with a sensing system that will "sniff" environmental conditions and selectively disseminate fire predictions to incident commanders and fire fighters in the field. Data assimilation and parameter estimation techniques will be used to address the need to reduce large dimensional sensor data to a parametric lower dimension suitable for rapid fire spread analysis, interpretation, and alert purposes, allowing for a more efficient (mobile) communication of events for decision-making and crisis management. Large-scale simulations will be devised, refined, and evaluated (on the massively parallel platforms available to the proposers when needed). The simulations include consideration of the physical geometry (e.g., in wildfires terrain, weather, vegetation) as well as parameters articulated from historical, observational, and sensory data. The Kepler scientific workflow system will be used to coordinate the execution of real-time data processing and fire modeling tools on distributed computing environments. Decision theory will be applied to identify time scales required for meaningful data assimilation (sensor, model, networks) so as to ultimately affect decision makers. Extensive testing of the concept of the super-real-time sensing and data-driven predictive fire models will be conducted in a virtual test bed [10, 39]. A data communication layer with links to archives, experimental data, and heterogeneous sensor data networks will be developed. The test bed would integrate portals for dissemination of data to different end users that include scientists, first responders, and public notification of user-defined real-time alerts via various receivers and Web 2.0–based public systems. This test bed will address the need for expansive data and sensor driven models, leading to predictive modeling assistance for decision makers.

Human Behavior Social science has shown that the response to sensor information and fire warnings varies dramatically with levels of social capital, demographic conditions, and historical experiences with similar warning systems [40–45]. The investigators will test the responses of both first responders and residents to our SNIFFR system through multiple approaches, including qualitative process tracing of past disasters (to better understand what factors are relevant), agent based modeling (to predict crowd and group behaviors in safe virtual environments), and field experiments of the technology. Evacuation rates and speed from residents along with response time and appropriate tactics from first responders will be used as core performance metrics. Once these metrics surpass those of current technologies, the SNIFFR system will be ready.

5.6.2.6 SNIFFR System Development

The SNIFFR addresses important fire scenarios as shown in Figure 5.1. In forest fires (time scale of days), the SNIFFR provides information to adapt for optimal resource allocation as conditions change. In complex buildings (time scale of tens of minutes), the SNIFFR locates hazardous conditions and directs occupants along safe evacuation routes. In transportation fires (time scale of minutes), the SNIFFR diagnoses the fire source and provides information to response systems for restoring the system to a safe state. Decision theory will be employed using IC expertise to construct decision-tree/influence diagram models for these scenarios. Further, sensitivity analysis on decision models will be performed to identify the most critical information flows. Finally, forecasting post-processing and visualization tools to best communicate ensemble predictions will be developed.

Forests The San Diego backcountry instrumented with the densest county-wide sensor array available in the world will serve as a test bed to analyze the SNIFFR effectiveness in protecting WUI. Archived weather data from this network will be compared with corresponding WUI fire simulation using the Kepler system (available at the collaborating San Diego Supercomputer Center and described in the Super-Real-Time test bed). Further, home ignition data from IBHS and NIST will be utilized to assess the realism and performance of the ignition behavior of the WUI fire simulations. The SNIFFR system must also address how the information will be interpreted and passed to incident commanders and individual emergency responders. Guidance for emergency responders will be addressed based upon the decision theory activities mentioned previously in this section.

Buildings The efficacy of the SNIFFR system to locate people, provide people with meaningful information, and propose evacuation strategies in complex buildings will be performed through a combined physical and virtual system test bed. Large-scale experiments would be performed at available facilities (e.g., at university or industrial partners) having mock-ups of multi-room spaces. Tests would be conducted monitoring fire conditions to evaluate the SNIFFR system detection algorithms in the incipient fire predictive performance in the developing fire. These fire tests would be extended to large-scale experiments in buildings with comparable footprints as high-rise buildings (historically available when scheduled for significant renovation or demolition). With regard to people, it will be important to understand human response to fire in complex buildings so that people can be provided with meaningful information and guided in ways that are readily accepted. SNIFFR communications will be evaluated in an available small-scale virtual reality (VR) "cave" where a subject (occupant or emergency responder), with VR goggles and perhaps other interactive feedback devices, navigates simulated game-like environments (of the full-scale building tests) with and without guidance from corresponding SNIFFR communications. Determining effective guidance for emergency responders will be addressed based upon the decision theory activities mentioned previously.

Transportation The transportation test bed will consist of three components: a ground vehicle, an aircraft, and a coal mine. The order of components corresponds to progressively larger and more complicated environments that will be used to test progressively broader ranges of the SNIFFR technologies. To implement the ground vehicle component, a decommissioned bus will be acquired and placed at the Maryland Fire and Rescue Institute training grounds. The SNIFFR sensing system will be installed in the vehicle, and its ability to diagnose incipient fires associated with simulated malfunction of electrical and mechanical components will be examined. The aircraft component will be based on a widebody aircraft mockup located at the fire testing facility of the FAA Technical Center. Experiments will be conducted in this mockup to establish the SNIFFR's capability to detect in-flight fires, forecast fire growth (based on sensor input), and communicate this information to the flight crew. The last component of the transportation test bed will be realized using the NIOSH coal mine fire testing facility. This component is selected to mimic fire scenarios in underground transportation infrastructure (i.e., subways and tunnels). Experiments designed to simulate accidental equipment fire, such as conveyor belt or electrical generator fires, will be conducted. The ability of the SNIFFR to detect these fires at early stages, correctly forecast fire development, communicate essential hazard information and tunnel environment to optimize egress will be tested and validated. It should be noted that the last two components utilize testing facilities of the organizations, whose goals are consistent with that of the SNIFFR. The proposed experiments will be incorporated into these organizations' routine test schedules to leverage their resources.

5.6.2.7 SNIFFR Impact

The SNIFFR workforce development efforts seek to build a stronger pipeline in engineering and science through innovative research training, university education, and precollege activities. This pipeline is essential for our stakeholders in general and advances in fire resilience technology in particular. The strong appeal of our exciting multidisciplinary test beds (e.g., SRT visualization or airplane test bed) will be used to attract undergraduate and PhD research assistants. Fire Protection Engineering undergraduate students will continue to be attracted to these research opportunities, and returning members of the military and existing members of the fire service will also be targeted for our doctoral programs. Upon graduation, these individuals will serve as the agents of change to revolutionize the traditional fire fighting industry. These students will intern at ERC member institutions and enrich cross-disciplinary projects. The nanoHUB framework will be utilized to create an "international learning network" FireHUB. The rich web-based features will be used to provide simulation tools for researchers, curricula, and activities for outreach to K-12 and community colleges, and NSF Research Experience for Teachers (RET) resources. A Young Scholars Program would leverage FIRST Robotics Competition for SNIFFR-enabled fire challenges building on the strong robotics and unmanned vehicle interests at partner and collaborating institutions.

The Innovation Ecosystem is the structure that enables technology and information to flow between individuals, companies, and institutions partnered within the ERC to foster the transformation of discovery into viable new offerings (i.e., innovation) for commercial economic growth [46,47]. The ERC will institute Industry and Practitioner (I&P) membership through financial commitments (and possibly other resources) with an Industrial Advisory Board. Semi-annual workshops with I&P members will continuously "pull" the ERC research agenda into focus while strengthening existing strong and functioning relationships (e.g., insurance, sensor and control companies) for champion-based recruiting. The networked sensors, insurance, and EFR sectors will be the first value chain target for ERC membership as these groups already have a high level of research engagement. Strong university-based innovation and entrepreneurial resources are available to drive the commercialization process at university and ERC partner institutions (e.g., MTech). Commercialization is critical to achieve a balance between the knowledge and commercial economies required for a sustainable ERC.

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CHAPTER 6

Data Collections

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Abstract

Existing database collections already provide important information used by today's fire service, not only on the fireground but in all aspects of their duties, including pre-fire planning, code enforcement, fire inspection, education, and investigations. Today, the evolution of cyber-physical systems is providing access to massive amounts of new available data. These databases address key operational parameters such as fire loss records, fire fighting resources, building information modeling, building supporting infrastructure, and so forth. Current and evolving data collections along with trends for future databases are an important consideration for Smart Fire Fighting.

Keywords

database
data collection
data

6.1 Overview

Responders today are facing increasingly complex and difficult incidents while serving their dynamic and multi-faceted communities. Since the advent of computer-aided dispatch, efforts to streamline and enhance incident response with data systems are being undertaken. Footprinted in these efforts are the challenges of an ever increasing myriad of responses. Designing updates and maintaining the complete data-supported framework of duties, as well as interrelationships with the response environment, is key to the data systems planned and utilized throughout the entire response community.

Phases of an incident (from pre-incident response, through the life of an incident, through recovery from the incident) are key in a discussion of the modern data collection and analysis system. Since the events of September 11, 2001, a national framework for response and recovery has been established, which gives us the framework for the discussions in this chapter.

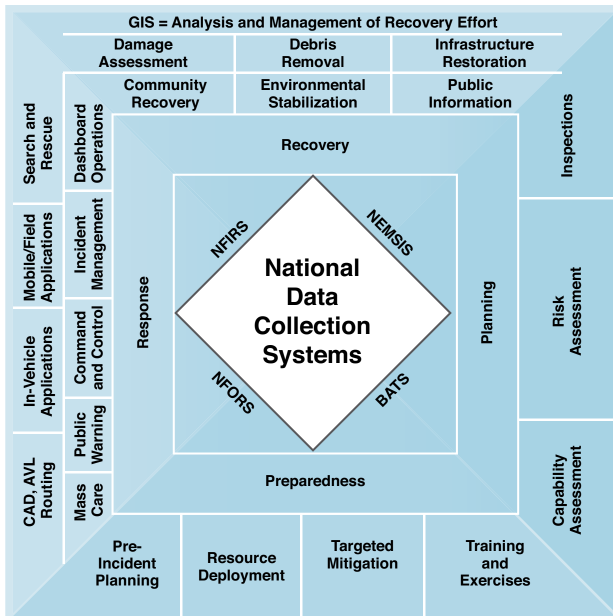
Utilizing the guiding principles of response in this chapter — planning, preparedness, response, and recovery — our discussions will shadow the efforts set out in the proposed NFPA guide NFPA 951, *Guide to Building and Utilizing Digital Information* (see Figure 6.1).

6.2 Planning and Analysis

6.2.1 Capability Assessment

Capability assessment data programs match real-world hazards and response assessments to the data packages within a community. Items such as analysis of travel times and station locations have been developed by utilizing well-established models of response such as NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression*

Figure 6.1 Planning and analysis.



Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments [1], and NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments* [2]. Capability assessment is a core method for evaluating the stakeholders' ability to react to potential all-hazards incidents.

6.2.2 Vulnerability/Risk Assessment

Vulnerability and risk assessments, as noted in the model shown in Figure 6.1, are core methods for evaluating stakeholders' liability. Assembled and aggregated, the vulnerability/risk assessment identifies potential loss and subsequent impacts to all stakeholders. Determining the magnitude and the types of incident potential builds on existing historical data sets and drives the investments in today's robust records management systems.

6.2.3 Inspections

Recent advances in inspection programs and inspection field performance assist the building of robust data inspection files. Such advances, along with mobile devices, create a higher level of performance code enforcement and building safety. Tablets and other mobile hardware, along with inspection software programs, are utilized to prearrange inspections, assist in the completion of the inspection, and then transmit the results to the local governmental agency and to the local responders. Hazardous materials and hazardous processes, supported by codes and code enforcement, complete the enhanced inspections systems in use today. A complete set of address data files and code compliance programs ties the field inspection work together into an address-based inspection file, which assists in the overall planning function with a set of data and analytical tools. Inspection efforts produce substantial amounts of data. Technology can be used to more efficiently collect, update, and manage the data. Technology can also be leveraged to distribute this important information to multiple stakeholders, thus increasing the efficiency of the process and the inspection system. Properly implemented technology can increase the overall safety while focusing limited resources to fill the greatest needs.

6.3 Preparedness

6.3.1 Pre-Incident Planning

Pre-incident planning plays a major role in the incident response as well as the emerging data environment. Pre-incident aspects and elements can be found in NFPA 1620, *Standard for Pre-Incident Planning* [3]. Pre-incident plans and target hazard planning have been the main focus of the "stack of notebooks" utilized by most departments today. Very large and, often, multiple notebooks are filled with pre-incident plans. As such, they are perfect for inclusion in the new data-enabled world in which we operate. In the beginning, computer-aided design (CAD) systems anticipated the need for pre-incident plans and attempted to provide rough building outlines and supplemental information. Due to their limitations, those early systems were unable to provide real-time replacement for the notebooks. Handmade drawings are carried in most apparatus today and are the mainstay of the pre-incident environment. Efforts are underway across the nation in progressive fire departments to utilize geo-based building CAD drawings, and some communities have made tremendous strides in this arena. A pre-incident planning process involves responder familiarization with specific site information, so this information is documented for use by responding personnel who might not be familiar with a specific site. Typical site information might contain access points, automatic systems controls, enunciator panel locations, and travel routes through the building (and complex). Technology can help streamline the acquisition and management of the data, which can be an important source of information during the initial response.

6.3.2 Resource Deployment

Resource deployment data systems utilize sophisticated analysis of time and distance. They also include an elaborate array of factors for analysis of turns, stops, and intersections. These systems can determine the best location for fixed-station assets and field units and compares them with real-word responses to validate the best allocation of resources for a community.

According to the ESRI white paper *GIS for Fire Station Locations and Response Protocol*, "Utilizing a fire station layer and street layer, response time analysis can be performed. A street layer is often represented in GIS as a series of lines that intersect on the map, creating a GIS street network. Each street-lined segment between intersections contains attribute information such as road type, distance, and travel speeds (miles or kilometers per hour). This allows users to identify a station location, specify a travel time, and run a network analysis. The result will be displayed by an irregular polygon around the station that illustrates where the apparatus could travel in any direction for the specified time. This type of analysis can be performed on a single station or simultaneously on all stations to analyze gaps in coverage, establish run orders, and more" [4].

6.3.3 Targeted Mitigation

NFPA 951 describes program management in the following manner: "Program management, targeted mitigation, and special projects include specific programs and projects identified during the planning analysis process. This can include special projects such as accreditation, the identification of equipment failure trends, or incident patterns. Technology, including spatial technology, can aid in the execution, implementation, and management of various programs and targeted programs" [5].

6.3.4 Training and Exercises

Multiple efforts have been made over the last few decades to vastly improve training and exercise capability within the emergency response community. NFPA 951 states, "Training develops skill sets needed to perform a function. Exercises are a practical application of skill development. Training and exercises help ensure that staff have the skills to access the appropriate information from the appropriate technology when it is needed. Additionally, as technological tools are implemented in the agency, much of the success of these tools will depend on proper training" [5]. Those efforts, such as online refresher courses, have produced valuable cost-cutting results. Mandatory refresher and retesting requirements within state-mandated emergency medical technical/emergency medical services (EMT/EMS) programs have encouraged online learning improvements. Continued development into the fire suppression and hazardous materials response arenas has been a logical expansion of the online efforts. The International Association of Fire Chiefs (IAFC) and the National Fire Protection Association (NFPA) offer online education leading to certification and accreditation as well as programs for responding to hydrogen incidents and electric vehicle incidents. Management and leadership programs utilizing advanced decision making with scenario-driven programs continue to be developed and implemented. Online learning programs that lead to certification, such as the Federal Emergency Management Agency (FEMA) courses ICS 100 through 700, along with the push for exercise design criteria, have dramatically restructured this entire subject matter.

Command and control training by simulators has been in place for decades, and the concept is thriving throughout the responder community. Computer-aided simulators utilizing advanced imagery are used not only for command and control training and keeping skills sharp but also throughout the industry as part of the testing process for promotion to company-level and above officer positions. Major investments have been made, and in some cases, structures have been designed and built specifically for this purpose. Facilitating intensive real-world incident command and control training, the simulator labs are proving to be an invaluable resource. Capturing multiple layers of data and utilizing street-level photographic systems, such as Google's street view, are contributing to the intensity, and real-world scenarios are being utilized at these simulator facilities. Testing after intensive training leads to enhanced fireground command and control and operational competency.

6.4 Response

6.4.1 Computer-Aided Dispatch, Automatic Vehicle Location, and Routing

Computer-aided dispatch, automatic vehicle location (AVL), and routing have all been supplemented by enhanced data systems. Improving the performance and capabilities of computer-aided dispatch has been the driving force for decades for the building of robust data-supported systems. Landline telephone data systems with automatic-number-identification/automatic-location-identification (ANI-ALI) and cell phone data components (locator requirements-GPS) drive the need for data interfaces to enable computer-aided dispatch systems to function at their current levels. AVL, coupled with advanced routing strategies, is currently in place in the United States and other developed nations. Smart computer-aided dispatch systems function by interfacing and integrating with multiple computing platforms and data systems. Often the computer-aided dispatch environment is interfaced with traffic routing and utilizes GIS layers to improve dispatch performance.

6.4.2 In-Vehicle Applications

As noted in NFPA 951, "Mobile devices allow responders to send and receive information in the field. Mobile devices assist responders in locating an incident, assessing the incident, and implementing a response. Mobile devices also provide on-scene information regarding the status of the incident" [5]. Utilizing off-the-shelf WiFi and cellular data systems allowed for the adaptation of mobile systems and continues to be used throughout the United States.

6.4.3 Mobile/Field Applications

Mobile field intelligence programs give responders real-time building information and video feeds from smart buildings to units in the fields. Complementing this effort is the movement toward building plans and pre-incident information programs that takes the "stack of notebook information" and pushes it forward to responding and on-scene units. Most of these systems operate with CD or hard drives with pre-loaded formats rather than relying on transmitted data. With the advent of FirstNet (National Public Safety Broadband Network), a major shift to central data storage and transmission systems is on the horizon.

6.4.4 Search and Rescue

Continuing with data collection systems as framed in NFPA 951, the next topic is search and rescue (SAR). "SAR is a multi-faceted process that ranges from finding the lost (search) to bringing them back to safety (rescue). Technology is an integral part of search and rescue operations. Many of the data sets used across the planning, preparedness, response, and recovery phases serve a critical role in SAR operations" [5].

6.4.5 Evacuation/Shelter/Mass Care

Evacuation, sheltering, and mass care data-enhanced systems have developed in dramatic fashion in the post-9/11 era and are coupled with emergency management efforts to give support to communities suffering from a disaster. According to NFPA 951, "Technology can support determination of suitable shelter locations and/or mass care operations, including supporting materials and power. Geographic information can be utilized to select shelter locations and route evacuated populations appropriately" [5]. Many of these systems have been fully implemented and have been utilized effectively for large-scale, real-world incidents. Statewide efforts continue to improve with use and investments. Modeling of those efforts and leveraging of the GIS platforms in use today in state governments and large municipal environments leads to continued improvement of data sharing and the capability of these programs. Web-based platforms have become an operational element and allow for enhanced response and recovery, as noted on the Missouri State Emergency Management Agency website: "SEMA [State Emergency Management Agency] and our response partners believe [a commercial web-based platform] provides the opportunity for leadership at all jurisdictions to work with a common operating picture and real-time situational awareness of events affecting their region and the state" [6].

6.4.6 Public Warning and Notification

NFPA 951 frames public warning and notification by stating the following: "Public warning and notification consists of four primary methods: public warning systems, telephony, media, and push notifications. Technology has a significant impact on all four of these methods through faster relay, target audience, and control of the message" [5]. Public warning and notification systems have also been privy to enhancement by data systems and social media efforts in various communities. Continued utilization will bolster these alert systems as they prove valuable in helping the stressed community. The app community is also fully engaged in public warnings and has become a critical component of the local news media, including most local TV stations. Apps have also been developed by response agencies to aid the public in locating automatic external defibrillators (AEDs) when reporting a sudden cardiac arrest to the 911 dispatch centers. Public alert/notification systems are commonplace and utilized and are becoming a new, even faster Cellular Neural Network (CNN) notification environment that first occurred in the early 1980s. Increased utilization of apps has completed the buildout of the public notification and warning systems found throughout the United States, which is supported by the local emergency management community. The apps systems, which are mostly associated with telephone push and text alert systems, are being leveraged by the response community in an almost linked fashion whereby the word and notifications occur in an almost real-time environment. Social media and their role are being routinely monitored by the response industry and are currently viewed in a mostly favorable light. Negative feedback on recent social media postings by responders has resulted in departments adopting rigid social media policy and procedures. A model social media policy can be found on the IAFC website.

6.4.7 Command and Control

Command and control systems have matured and will continue to do so with improvements and investments. As mentioned earlier, with today's computer-aided dispatch backbone and RMS, traffic, and AVL systems, the systems are coming together with real-time fire fighter resource tracking during an incident. The focus on fire fighter tracking and the multimillion dollar investment in these systems have started to produce effective scene-management programs. Most notable of these systems is Geospatial Location Accountability and Navigation System for Emergency Responders (GLANSER) and the research done at Worcester Polytechnic Institute (WPI). Looking to the future, these systems will become an essential layer for a command and control module and a key component of the incident management system. Command and control environments will mature in the next decade and, along with the National Incident Management System (NIMS), will be easily adapted to multi-jurisdiction responses. These efforts will be greatly enhanced with the build out of the FirstNet system. CAMEO and ALOHA (plume modeling tools) can be accessed online at the U.S. Environmental Protection Agency (EPA) website and the U.S. Department of Transportation (DOT) *Emergency Response Guide* (transportation-based hazardous materials action guide) can be accessed online at the DOT website. Both are prime examples of incident (hazardous materials incident response) tools available online. These types of supported systems will continue to mature, and the response community will be able to utilize a complete suite of operational and decision-making tools online.

6.4.8 Incident Resource Management

As already mentioned, **data collections** and data-enhanced tools and programs are leading to effective resource management. This emerging environment can be and is being adapted to large, multi-state efforts in which effective resource management is key. For decades, the Resource Ordering Status System (ROSS) has provided a mainframe approach to the wildland fire community for ordering assets during a large-scale wildland fire incident. In addition, Mutual Aid Net and other federally funded programs utilize web-based systems for both in-state and between-states assistance during times of disasters. Multiple agency efforts are also underway in Illinois, with Mutual Box Alarm System (MBAS), which is enhanced with an elaborate data system that tracks assets throughout its division.

6.4.9 Multidisciplinary Coordination

Framed in NFPA 951, multidisciplinary coordination is described as follows: "Through the use of relational data, an integrated information system becomes an ideal platform for enhancing situational awareness and supporting collaborative decision making for events requiring multi-agency and multi-jurisdictional coordination" [5].

6.4.10 Operations Dashboard

The concept of operational intelligence is key to a modern data collection system and, as such, is looked at by NFPA 951 in the following manner, "Technology synthesizes information from different and often disparate systems and delivers it to various platforms. This intelligence provides critical support for decision making throughout various functions of the organizations" [5]. Data mining and web tools that utilize the cloud and other cloud-framed environments are reshaping modern data collection systems. Movements are being made to access data stored by external means rather than in-house management and retrieval of the data. Doing so allows for a major reduction in the operating costs of modern data collection systems and is reshaping responder records management approaches.

6.5 Recovery

6.5.1 Damage Assessment

Critical to the management of a major incident is the damage assessment component. Recent large-scale natural and man-made disasters have provided the emergency management community the opportunity to readily test GIS-based damage assessment tools for reporting and updating. Completing this task in a timely manner is greatly enhanced by GIS and parcel valuation systems currently being used by most local governments throughout the United States.

6.5.2 Debris Removal

Web-based debris removal tracking systems vastly improve reporting accuracy and recovery efforts. Keeping individuals posted on debris removal progress greatly improves communication to those affected by an incident. Posting daily clean-up activities via mapping, along with daily press briefings, produces an improved relationship with those affected by the incident and the post-recovery efforts.

6.5.3 Infrastructure Restoration

Infrastructure restoration and issues such as power outages are a major area of concern. Knowing when the power is going to be restored allows individuals affected by an incident to better plan their needs. Power restoration is often essential to allow for re-entry into an evacuated area, and medical support systems are often dependent on the power grid. Because the life support environment has moved into the home, power restoration truly takes on a life or death meaning. Supporting refrigeration and in-home medical devices is critical. As such, decisions need to be made for restoration activities and care support decisions. Data-enhanced systems, along with the information they provide via the web, take on increased importance during times of distress. Snow storms, ice storms, and wild fires all have the ability to interrupt the power grid and thus can disrupt in-home medical support systems. Accurate power restoration data systems continue to improve and, in doing so, support responders in the recovery phase of an incident. Sense of normalcy and progress of recovery are often associated with power restoration, and providing accurate and timely information is vital for the mental health of a community, as well as the physical recovery, during the recovery phase.

6.5.4 Economic and Community Recovery

During the event cycle, economic and community recovery is a component that can be enriched with data collection systems. Data systems, as well as social media and the ability to communicate with those affected by the incident, support economic and community recovery by letting people know that a business or a section of an area has returned to an operational level. This signal can be the start of the economic engine post-incident recovery phase. Plotting data and mapping all recovery efforts on GIS produces mapping, which can be conveyed to affected businesses. Economic recovery and infrastructure replacement go hand in hand and are perfect for mapping and plotting to convey the speed of recovery to support restoration efforts.

6.5.5 Environmental Stabilization

The topics of economic and community recovery and environmental stabilization loom large in most natural disasters and can be a major factor during a man-made disaster. NFPA 951 frames environmental stabilization in the following manner: “If an incident or response activities result in a disturbed environment, damages from such disturbances must be mitigated and the environment must be stabilized to reduce future damage. Mobile devices are often used to document and catalog needed rehabilitation/stabilization activities, while GIS software provides for visualization, prioritization, and process tracking. Spatially enabled models provide impact analyses to determine the activities necessary to reduce the risk of future damage” [5].

6.5.6 Public Information

Essential to the recovery phase is the conveyance of recovery information to the public. NFPA 951 utilizes the enterprise approach for its discussions on public information: “Information can be published in many forms to facilitate transparency, encourage communications, and engage the public. Access to accurate information about the status of an incident, shelters, and access to supplies and services can be managed, maintained, reported on, and published in an enterprise data base. Notification of ability to return, return routes, damage assessments, and reporting requirements (e.g., FEMA, insurance) can also be provided” [5].

6.5.7 Analysis and Management of Recovery Efforts

NFPA 951 looks at the analysis and management of recovery efforts from the perspective of the GIS platform. Framing these components, NFPA 951 provides the following description: “The analysis of recovery efforts can integrate information using dynamic data, including incident locations, unit tracking, traffic, weather, and other relevant data. The product of the analysis can be queried based on various attributes including incident type, cause, time, units assigned, or other attributes. With a geo-spatial framework, organizations can manage the recovery efforts visually. This allows for incident analysis to be done quickly, displayed logically, and understood easily” [5].

6.6 National Incident Reporting Systems in Use or Under Development

6.6.1 National Fire Incident Reporting System (NFIRS)

URL: http://www.usfa.fema.gov/fireservice/nfirs/index.shtm

NFIRS 5.0, All-Incident Reporting System, is designed to keep pace with the rapidly changing activities of the fire service. The system is designed to include fire, emergency medical service (EMS), hazmat, wildland, and arson incidents. Inclusion of new incident types is also supported. The standard promotes uniformity of incident reporting by establishing the NFIRS 5.0 coding methodology.

The following facts about NFIRS were taken from the U.S. Fire Administration (USFA) website (July 2014):

- The NFIRS represents the world's largest, national, annual database of fire incident information.
- State participation in NFIRS is voluntary.
- 50 states and the District of Columbia report NFIRS data.
- 37 fire departments in communities with protected populations of over 500,000 participate in the NFIRS.
- Nationally, about 23,000 fire departments report in the NFIRS each year.
- Participating departments report an average of 23,000,000 incidents and 1,000,000 fires each year.
- The NFIRS database comprises 75 percent of all reported fires that occur annually.

The NFIRS has two objectives: (1) to help State and local governments develop fire reporting and analysis capability for their own use and (2) to obtain data that can be used to more accurately assess and subsequently combat the fire problem at a national level. To meet those objectives, the NFIRS provides the following:

- Incident and casualty forms
- A coding structure for data processing purposes
- Manuals
- Computer software and procedures
- Documentation
- A National Fire Academy training course for utilizing the system

Participating local fire departments complete Incident, Casualty, and optional reports for fires and other incident types as they occur. The departments then forward the completed paper forms or computer files to their state office, where the data are validated and consolidated into a single computerized **database**. Feedback reports are generated and forwarded to participating fire departments. Periodically, the aggregated statewide data are sent to the National Fire Data Center at the USFA to be released and included in a national database.

6.6.2 National EMS Information System (NEMSIS)

URL: http://www.nemsis.org/

The primary goal of the NEMSIS project is to create a repository of standardized EMS data from every state in the nation. The NEMSIS project provides electronic EMS documentation, an EMS information system for the states, and a national database with reporting capabilities.

Several benefits are realized from participation in NEMSIS:

- *Standardization.* Standardization makes it possible to aggregate data at the local, state, and national levels. The data can be used to improve procedures and patient care.
- *A business model for the EMS community*. Objective data help design protocols, create budgets, evaluate performance, compare across states, and benchmark standards of care.
- *Fee schedules and reimbursement rates*. Information can be used to determine national fee schedules and reimbursement rates, facilitate cost-benefit analyses, and help provide links with patient outcomes for financial analysis.
- *Policy and funding*.
- *Education and training*. Understanding the data helps prioritize the EMS curriculum and improve the education system.
- *Evaluating patient and EMS outcomes*. Researchers can use the data to determine what treatments are effective, reduce errors, and identify unmet needs.

6.6.3 National Fire Operations Reporting System (N-FORS)

URL: http://911perform.org/n-fors/

Unlike the NFIRS project, which was designed to track the incidence of fire, N-FORS was designed to track a fire department's response to an incident. The operational data elements are not included in the NFIRS database.

According to its website, the primary goal of the N-FORS project is to create a reporting system that empowers local fire departments to measure and optimize their response availability, capability, and effectiveness of on-scene performance. These operational measurements are directly connected to the outcome of the incident for the fire fighter, citizens, EMS patients, or property. The system is not intended to replace NFIRS but to provide fire departments with additional information to maximize safety and operations from an outcomes perspective.

Currently, the project is a data collection system that has been in development since 2011. The project is focusing on data reports and software to prepare for a pilot rollout in 2015.

6.6.4 Bomb Arson Tracking System (BATS)

URL: https://www.atf.gov/applications/bats/

The BATS tagline is "Your solution for a national, shared database of explosives and arson incidents available on the web around the clock."

According to its website, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) is a law enforcement agency in the U.S. Department of Justice. Its mission is to protect communities from violent criminals, criminal organizations, the illegal use and trafficking of firearms, the illegal use and storage of explosives, acts of arson and bombings, acts of terrorism, and the illegal diversion of alcohol and tobacco products.

The ATF developed BATS, a web-based case management system to handle arson and explosives investigations. As with other systems, it is made available to all jurisdictions and provides unified access to incidents at a national level.

BATS provide search functionality to facilitate access to data and to discover trends, patterns, and leads. BATS also connects agencies to the U.S. Bomb Data Center (USBDC), which maintains the national repository of arson and explosives incidents.

BATS and NFIRS are separate programs and implement different systems. The objectives, however, are complementary. NFIRS was designed to collect fire incident information, while BATS is dedicated to documenting follow-up investigations (i.e., case management). The two systems were designed to co-exist.

6.7 Looking Forward: Data Collection at the Local Level in a Unified and Scalable "System of Systems"

6.7.1 Toward a Unified, Agile Solution in Emergency Data Acquisition, Retrieval, and Reporting

No doubt, there is a need to build emergency reporting systems at a national level and make them available at the state and local levels. A unified view of the data can be used by investigators to connect the dots and for researchers to study how procedures, equipment, and training can influence outcomes and costs. A unified system can also greatly reduce the cost of developing and operating such systems. Intelligent use of data will ultimately reduce incidents, improve outcomes, reduce costs, and save lives.

Unified systems, however, can easily become too large and too complex to manage, resulting in long development cycles and possibly project failures at a great cost to taxpayers. There are multiple examples in which large projects designed for public and private organizations succumbed under their own weight.

This chapter described four separate systems designed to unify various aspects of data management in public emergency and response organizations. A great amount of highly specialized domain knowledge is required to build such systems, but this knowledge is not well utilized if local organizations do not adopt and use the systems.

The challenge is to use domain knowledge intelligently, without creating multiple custom systems. While a decentralized approach is necessary for each agency to address specific problems related to their missions, it would appear to be greatly inefficient to create disparate systems whose underlying structures are very similar.

It would seem that a single underlying system could satisfy the requirements of all agencies. Each agency, however, would use its domain knowledge to create the content and publish it to the unified system. In other words, agencies can benefit from an open standardized system for reporting, data gathering, and data retrieval. There is a risk, however, that such a centralized system will never see the light due to multiple requirements coming from multiple sources. Attempting to create a monolithic system to blindly satisfy all stakeholders will make the project unmanageable.

A unified system must be lightweight and built organically as a combination of multiple subsystems and applications. Interoperability must be central to the design, and independent agencies must be able to publish content and workflows with minimal effort. The design should be technology agnostic because technology changes quickly. For example, entering data related to a fire incident can be done manually on a web browser or directly using sensors and automatic systems. The system must be capable of growing organically and quickly without a major redesign. At all costs, we must avoid creating separate systems that cannot talk to each other.

Having disparate emergency reporting systems discourages emergency personnel from using them, especially if they are expensive to adopt and difficult to use. Usability must be a priority. For example, if at all possible, data should not have to be entered manually. Emergency personnel must be able to use consumer smartphones to access the system. Modern mobile devices are inexpensive and equipped with multiple sensors. Cost will keep dropping and functionality will be richer. We must take advantage of this trend for data collection. Smartphone data from incident locations can be automatically acquired and analyzed in real time without any human intervention. In addition, low-cost sensors mounted on equipment and buildings can constantly provide data. Moreover, automatic incident awareness can be used in such a way that all incidents are automatically reported if emergency personnel use a mobile device with emergency response applications. When an incident is reported, local agencies will then be prompted to fill out additional information manually. If data entry is kept to an absolute minimum and is consistent, emergency personnel are more likely to respond and provide valuable details that otherwise might be lost.

To manage complexity, the system should be as simple as possible. Decision makers must focus on core solutions and resist requests to add functionality. Any functionality that can be handled by separate application systems must not be included in the core. This approach will make it possible for the system to grow organically and will reduce development cycles.

It is also important to separate the human-computer user interface from the underlying structure of the system. The back end must be modular and communication done using application programmer interfaces (APIs), as is typically done in modern Internet systems. The back end does not need to know how a message was sent. For example a message reporting smoke may have been sent by a sensor, by a specialized application, or from a text message. The message will need structure before it is handed to the back-end system, but it must be flexible. Later, a researcher might study how the messages arrived and what messages were more effective. Perhaps there is a type of sensor that can detect an incident more efficiently than other sensors.

So what is the minimal required core system? The following section is a high-level view of how various components can work together in a minimal system.

6.7.2 A Minimal Open Core Data System

Agencies use domain knowledge to design structured documents that include the information required to record and later analyze an incident. The document structure helps computers transmit, store, and analyze the data. They should be simple for humans to create with a simple text editor or specialized software. Computers can also create and send documents automatically, for example, by using sensor data.

A document has fields such as time, location, personnel involved, duration of the incident, outcome, and so forth. The unified system will ingest the documents and create the associated functionality to perform the following functions:

- store documents
- query documents of any type
- have user interfaces so data can be entered manually from multiple devices (web, phones, tablets)
- send and receive the document via APIs

Such a system can be built efficiently using standard open-source software projects, many of which are supported by companies that provide enterprise-level commercial services. Using standard open-source components not only reduces cost in the short term but also makes it easier to maintain and improve the system over time without depending on specific vendors or proprietary software. Furthermore, the entire code base can be made open source to help other areas of government and gain community support. Community support helps create an ecosystem of developers and companies that can help fix bugs quickly and build applications around the common core.

When a high level of standardization is achieved on the core system, the doors will be opened to developers to build applications in a competitive market, similar to those found in the iOS and Android ecosystems. This level of openness aligns the interests of the various governmental jurisdictions, the emergency response communities, independent developers, software development companies, hardware designers, data scientists, and citizens. Ultimately, broad support from stakeholders is the best way to guarantee that the project will be successful.

Since standardization can be a lengthy and controversial project, it is important for the national emergency agencies to design and launch a minimal core system, simple enough to build quickly and flexible enough to allow for the broader community to help it grow organically over time.

A minimal, open-core data system not only promises to change how software is built and maintain in the emergency response community, but can also change the way government adopts new technologies by leveraging the best minds in science and technology.

6.8 Conclusion

Enhanced pre-incident response, response, and post-incident concerns are the new Smart Fire Fighter, data-enabled environments. However, utilizing these tools in an effective manner will require some maturing and testing of the systems to produce a truly smarter environment for responders and their communities. It all began with computer-aided dispatch and the ability to utilize data to dispatch assets to an incident.

Computer-aided dispatch and integration of elements such as fire fighter and vehicle tracking have tested our commitment to the Smart Fire Fighter environment. It is a work in progress, but the report card to date is very favorable. Lacing and integrating all these elements into a cohesive, real-world system of systems has begun in earnest.

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CHAPTER

7

Hardware/Software

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Abstract

The paradigm of cyber-physical systems (CPS) and the notion for Internet of Things (IoT) unlock the potential for looking at hardware and software as collaborating media. For smart and effective fire fighting, the mutual interchangeability and interoperability between hardware and software components is a must. An intelligent and open design of both commodities makes the processing of data and computation meaningful for fire operations in the field.

This chapter is divided into four main parts. It includes a description of (1) the current hardware practices as the fire fighter's equipment, (2) the areas of CPS paradigm particularly useful for Smart Fire Fighting, (3) the roadmap elements to achieve efficient and maintainable hardware and software collaboration, and (4) potential opportunities to realize this roadmap.

Keywords

hardware
software
interoperability
protocols and interface standards
simulation
computation
actionable intelligence

7.1 Introduction and Content

The paradigms of cyber-physical systems (CPS) [1, 2], industrial Internet [3–5], Industry 4.0, and the notion of Internet of Things (IoT) [1, 2] create an opportunity to look at **hardware** and **software** as modalities collaborating through the power of **computation**. This chapter takes on this challenging vision and explores concrete examples used for fire-fighting operations and in emergency response.

In particular, first, a review of the current hardware applied in fire-fighting operations is provided. Also, lessons learned from introducing new hardware into the fire-fighting industry are described. Then, CPS and IoT advances are analyzed to find out what they offer on top of today's state of the art on the hardware and software interface. A concrete example for a successful prototypical application of a CPS in the form of a Smart Emergency Response System (SERS) is introduced. Using this example, the technological research roadmap elements for the next five years are identified. The human-in-the-loop aspect and the coordination between multiple stakeholders are analyzed. Finally, select incentives to empower the execution of this roadmap are introduced.

To set up the context of this chapter, the definition of a CPS is introduced. CPSs are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components [6]. The National Science Foundation claims that advances in CPS will enable such capability, adaptability, scalability, resiliency, safety, security, and usability that will far exceed the simple embedded systems of today [1, 6]. The notion of CPS with the underlying IoT may indeed transform the manner in which people make use of the engineered cyber and physical systems.

CPS as a field of study is just beginning to receive traction and many challenges remain, as discussed in [1, 7]. The application of CPS as a means to achieve Smart Fire Fighting is clearly multifold and depends on the specific scenario type. On the one hand, a fire fighter represents the human-in-the-loop aspect that must be considered when designing smart systems. Thus, any hardware equipment and the human–fire interaction is a subject of study in this chapter. On the other hand, fire occurs in various forms, as wildfire, facility fire, private property fire, or indoor fire. Each scenario requires a different type and scale of treatment.

The CPS notion offers an open design to embrace the scenarios under investigation as a coherent and consistent entirety. This mindset forces the multidisciplinary collaboration to become reality and allows for dynamic changes in configurations in real time. Therefore, CPS is frequently called a system of systems [7].

Architectures for open systems are still under development [7]. CPS has to meet the demanding performance constraints of hard and soft real-time embedded operations of the collaborating software and hardware. These constraints become even more challenging when shared and when new functionality emerges while setting up new configurations. Hence, developing platform and communications technology stacks that are flexible and extendable becomes a necessity. These should support continuous evolution rigorously to enable a broad range of features with potentially safety-critical implications [8, 9].

Challenges also remain in specific design methods for CPS. The business value of these design methods has to still be evaluated and validated. This open nature of CPS implies that no one system integrator is responsible for the ultimate behavior of the system. This is a departure from standard design approaches where often a single original equipment manufacturer (OEM) assumes such responsibility. By collaborating in an open structure, the combined behavior of each of the constituent systems produces an emerging behavior that is not encoded a priori as a global system behavior [8]. As a result CPSs are always active and always reconfigurable. Their robustness is a challenge to be addressed, if not even certified. Operating in an uncertain but manageable environment, the ability to replace the failing mode, and environmental disturbances and other side effects are just a few obstacles to be named when designing a reliable CPS.

In the following section, the analysis of hardware/software **interoperability** focuses on the fire fighter who represents the human in the loop in a CPS design.

7.2 Hardware/Software and Interoperability: A Fire Fighter Perspective

There are approximately 1.1 million fire fighters [10] in 30 thousand fire departments [11] throughout the U.S. Every year there are approximately 30 million total emergency calls [12], approximately 1 million of which involve hazardous materials. Because fire fighters are first responders, an emergency call could involve any number of possible scenarios, such as a fire, an explosion, a residential gas leak, a motor vehicle accident, a railroad or airplane accident, a hazardous material (hazmat) spill, a structural collapse, or a medical emergency.

7.2.1 Hardware

A responding fire fighter will wear turnout or "bunker" gear, including a jacket, pants, gloves, a Nomex hood, a helmet. and a self-contained breathing apparatus (SCBA). The SCBA consists of a frame, an air cylinder, pressure regulators, hoses, a mask, and accessories that may be stand-alone attachments or may be fully integrated. Accessories to the SCBA may include a pressure monitor, an end of service time (EOST) alarm (sometimes called a low-air alarm), a personal alert safety system (PASS), a heads-up display (HUD) in the mask, a voice amplifier, a central power supply for electronics, a telemetry system, an accountability system, a land mobile radio (LMR), environmental sensors, a biometric monitor, an electronic heater or cooler, a global positioning system (GPS), or a tracking or location system. Since most of the SCBA accessories include electronic circuits, they could be categorized as electronic safety equipment (ESE).

Depending on the specific emergency scenario, the fire fighter may carry specialized tools, such as a Halligan bar, an axe, a fire hose, a rope, a thermal imaging camera (TIC), a video camera, a gas monitor, a pager, a cell phone, a flashlight, a positive-pressure ventilation (PPV) fan, a wire cutter, a drill, a jack, extrication tools, a listening system to find trapped victims, saws (K-12, SawsAll, etc.), or surveying equipment for collapse scenarios (e.g., transit, a theodolite, or a total station). Many of the tools could be considered ESE.

First responders who provide emergency medical services (EMS) may carry specific medical equipment, such as an AED/defibrillator, a ventilator, a motorized cot, a laryngoscope, a pulse oximeter, a blood pressure monitor, a thermometer, an electrocardiogram system (EKG), or a CO_2 monitor. Virtually all of the medical equipment would be considered ESE.

Fire apparatus provide transportation of fire fighters, water, and equipment to an emergency scene. Apparatus may include an engine or pumper, a ladder truck or aerial apparatus, a heavy rescue vehicle, a wildland fire vehicle, a hazmat vehicle, a tanker truck, an EMS vehicle, and a command support vehicle. Heavy rescue vehicles are primarily designed for technical rescue situations, such as extrications from vehicles, confined spaces, or trenches, or rescue from swiftwater or building collapses. In small departments, a command support vehicle may simply be the chief's SUV; in large departments, it may be a large mobile command center with multiple radios (including satellite links) and closed-circuit television (CCTV) for monitoring, with provisions for use as a conference center for command personnel for mapping and planning fire-fighting operations and booking and directing crews as they arrive on-scene.

Electronic safety equipment on fire apparatus would include communication equipment (base radio, public address system, intercom, etc.), alarms (siren, back-up alarm, etc.), navigation equipment (GPS, base station for locator, etc.), monitoring equipment (CCTV, environmental sensors, computer and video monitor, etc.), and other miscellaneous equipment (battery chargers, microwave oven, refrigerator, electrical generator, personnel heater, etc.).

Most of the electronic safety equipment carried by fire fighters and fire apparatus include some form of software, with most of it being embedded code in the particular piece of electronics.

7.2.2 Component Attributes and Certification Standards

Many of the components carried by fire fighters would be considered life safety equipment, meaning that their performance could directly affect the life and safety of both the fire fighters as well as civilians. Consequently this equipment must meet minimum standards for reliability, operability, maintainability, durability, availability, and stability. For equipment used by fire fighters, the governing standards are developed by National Fire Protection Association (NFPA) Technical Committees (TCs) under the direct guidance of the NFPA Correlating Committee, whose responsibility is to ensure compatibility between standards generated by different TCs. Each of the standards cover the design, performance, and testing for particular equipment. For example, NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services,* is prepared and maintained by the Technical Committee on Respiratory Protection Equipment; NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*, and NFPA 1801, S*tandard on Thermal Imagers for the Fire Service*, are prepared and maintained by the Technical Committee on Electronic Safety Equipment. NFPA 1802, *Standard on Land Mobile Radios*, is currently being drafted by the ESE TC. There are currently no other NFPA standards on ESE, although more are anticipated in the future.

The various NFPA standards provide the requirements for operability, durability, and stability for the equipment. Maintainability is generally not specified, and it is up to the user or manufacturer to keep the equipment functioning properly during its expected lifetime, which is typically 5–10 years. Availability is dependent on the particular fire department having access to the equipment.

There are no specific requirements for reliability, except to the extent that the testing methods in the various NFPA standards are designed to ensure an acceptable level of reliability; after specific tests, the units are required to perform as defined in the standard. The first NFPA standard for ESE was NFPA 1982 (PASS), which serves as the model for later NFPA standards. Several of the test methods are noteworthy. For example, the heat and flame test requires the unit to be first soaked at a temperature of 95°C (203°F) for 15 minutes, followed by exposure for 10 seconds to direct flame. For the heat and immersion leakage test, the unit is soaked for 15 minutes at a temperature of 177°C (350°F) and then immersed for 15 minutes into water at a temperature of 18°C (64°F); the heat/immerse cycle is repeated for a total of six times, at which point no water should be found inside the unit. For the high temperature functionality test, the unit is exposed for five minutes to a temperature of 260°C (500°F); following removal from the oven, the unit must function normally. For the tumble-vibration test, the unit is placed in a rotating cylindrical apparatus much like a large clothes dryer and tumbled for a period of three hours; after the abuse, the unit must function normally.

7.2.3 Interoperability

Interoperability of equipment must be done in several "directions" using multiple mechanisms. "Vertical" interoperability would involve different subsystems on the same entity, whereas "horizontal" would involve the same subsystem on different entities. For the individual fire fighter, vertical interoperability would involve the various pieces of equipment in the fire fighter's ensemble, particularly if the equipment is considered integrated. Vertical interoperability for fire apparatus would involve interaction among all of the subsystems on the particular vehicle.

Horizontal interoperability would involve the interaction between such combinations as:

- Fire fighter to fire fighter (voice communication, status, 3D location or relative location, etc.)
- Fire fighters and the incident command center (voice communication, telemetry, command/control, status update, etc.)
- Fire apparatus and the incident command center (voice communication for logistics and status, command/control for moving apparatus, deploying aerial ladders, etc.)
- Fire fighter and fire apparatus (voice communication, location, etc.)
- Incident command center and fire station (status, command/control, request for more personnel and equipment from dispatch, etc.)
- Fire fighter and fire station (voice communication, status, etc.)
- Incident command and command station(s) (voice communication, command/control, status, particularly for larger incidents)
- Incident command and police (requesting assistance for snipers, traffic control, etc.)
- EMS apparatus and hospital (data transfer for monitoring patients, preparation for medical procedures, diagnosis and treatment by hospital MDs during transport, etc.)

Interoperability would include electrical mechanisms, such as wired, wireless using radio (RF-based), or optical, as well as mechanical mechanisms, such as physical, pneumatic, hydraulic, or acoustic.

As an example of vertical interoperability for a fire fighter, consider a PASS device that is integrated into the SCBA. The first versions of PASS devices, circa 1980, included a motion sensor and a loud alarm; if the fire fighter became incapacitated and remained motionless for a period of time (typically 30 seconds) the alarm would be activated, thus notifying other fire fighters of the victim's situation. These early devices needed to be turned on with a mechanical switch. When it became apparent that not all fire fighters in the heat of battle remembered to turn on their PASS device, an alternate activation method was implemented: an activation clip (which would be tethered to the fire apparatus) would automatically turn the unit on when the SCBA was donned by the fire fighter. While this solved the initial turn-on problem, another issue surfaced: after using the SCBA at the fire scene and putting the unit down to take a rest, the PASS alarm would turn on again after 30 seconds. The solution was for the fire fighter to carry an extra activation clip to silence the alarm. However, if the unit was reused, the fire fighter could again forget to turn on the PASS device. The ultimate solution was to activate the PASS device by means of a pressure switch connected to the SCBA air supply: as long as the air valve was open, the PASS device would be automatically turned on. Interoperability for this situation would be considered pneumatic.

At fire scenes, fire fighters typically operate as two-man teams for fire attack or primary search, using a "buddy system" for safety and accountability. Fire fighters will often operate as two-, four-, or six-man rapid intervention teams or crews (RIT/RIC) for rescue operations. Horizontal interoperability for such teams would include at a minimum the ability to communicate with other members of the team. Figure 7.1 illustrates some of the possible paths for interoperability at an emergency incident.

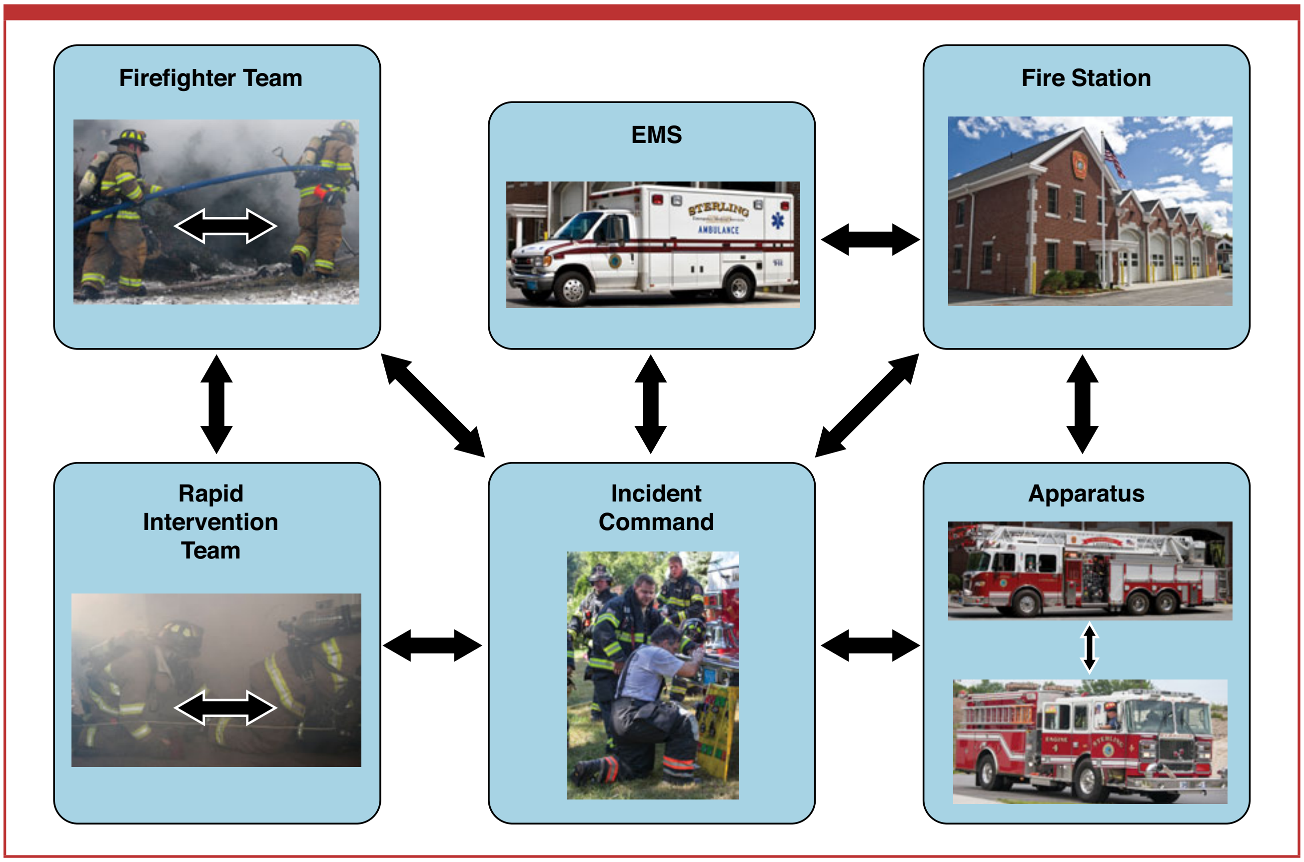
7.2.4 Interface Standards

At present, telemetry data protocols are defined by the individual manufacturer; very little work has been done to standardize the protocols so that equipment from one manufacturer would be interoperable with that of another manufacturer. However, as more equipment becomes integrated under the Smart Fire Fighter program, input/output **protocols and interface standards** will need to be defined. Incorporating the requirements into the specific NFPA standards would seem to be the best way to ensure that all manufacturers adhere to the same protocols and interface standards.

7.2.5 Scale of Interoperability

One issue, particularly for vertical interoperability, involves the scale of the entity. One might argue that interoperability would apply to the complete scale from system and subsystem down to the component level. For example, perhaps the interoperability requirements for individual components — such as resistors, capacitors, or sensors — would need to be

Figure 7.1 Interoperability at emergency incident. (Source: Courtesy of the Sterling, MA, Fire Department — Photographer Tina Gianos.)



specified. The implication is that a manufacturer would then be able to verify that a particular component could be used as a substitute in a subsystem or system without loss of performance.

In reality, several issues serve to limit the scale for specifying interoperability. The process by which systems are tested and certified to specific standards (NFPA, NIOSH, etc.) generally applies to a complete system and as a result prevents further division of the scale. This process requires the system — complete with any accessories — to operate as a whole entity. If someone replaced a subsystem, component, or accessory, then generally speaking, the system would no longer be certified to the particular standard. Such action would potentially lead to product liability and possible legal action if an injury occurred to a fire fighter who was using the particular system; legal ramifications would apply not only to the person or company who made the replacement or attached the accessory, but also to the fire department and/or the municipality that allowed the modification.

The situation is further complicated by the fact that only the original equipment manufacturer (OEM) can request that a system be certified to the standard; this prevents a second manufacturer from substituting a component or subsystem or attaching anything as an accessory without the express approval of the OEM; without such approval, the OEM would likely void any warranties should such action occur. The second manufacturer would also be potentially liable for any injury for the complete system even if it replaced or added only a small portion of the total system. History has shown that when injuries occur, the advocates for the injured party assume everyone is liable, and those involved in the manufacture or use of any product that might have been in use will attempt to shift the blame to others. Under the current certification climate, the only viable option for a second manufacturer would be to work closely with the OEM, in which case the specifications for performance would be established between the two companies.

In today's certification environment, the scale of interoperability would thus be restricted more to the system or possibly subsystem level rather than to the component level. For stand-alone systems, such as thermal imaging cameras, further division would generally not involve interoperability. However, this distinction would become somewhat blurred if the unit were to communicate to other devices, such as a base station, by transmitting video through an RF link. To maximize interoperability, it would be necessary for the device to use a standardized communication format. The situation is similar for land mobile radios (LMRs).

To make it possible to have maximum interoperability, the present company-specific system designs would have to be replaced with a broader design paradigm, along the lines of the current NFPA specifications that companies now meet with their own specific design philosophies — this would necessitate specifications for subsystems that each company must meet in their own way. Only then would fire departments be able to replace individual subsystems from different companies and still have a fully interoperable system. To be effective, such a paradigm shift would need to be implemented by the NFPA TCs. A number of practical impediments to this approach, such as mechanical packaging and environmental testing, would need to be resolved.

7.3 Case Study to Present the Technological Research Roadmap

While the previous section focused mainly on a sophisticated hardware as a basis for a fire fighter's "exoskeleton" and operations in the field, this section takes a case study of a futuristic emergency response system and breaks it down to its unit ingredients. The future trends are analyzed while stepping back through the elements of the Smart Emergency Response System (SERS). A research agenda is being established. In particular, internal and human-in-the-loop aspects are considered. External aspects in terms of coordination between multiple hardware and software components providers are illustrated. A technological and research roadmap indicates where the SERS prototype should be improved and where there is an area for development.

7.3.1 The Smart Emergency Response System (SERS)

The Smart Emergency Response System (SERS) prototype was built in the SmartAmerica Challenge 2013–2014, a United States government initiative [13]. SERS has been created by a team of nine organizations led by MathWorks. The project was featured at the White House in June 2014 and described by U.S. Chief Technology Officer Todd Park as an exemplary achievement [14]. The SmartAmerica initiative challenges the participants to build cyber-physical systems as a glimpse of the future to save lives, create jobs, foster businesses, and improve the economy [13]. SERS primarily saves lives.

The system provides the survivors and the emergency personnel with information to locate and assist each other during a disaster. SERS allows users to submit help requests to a MATLAB®-based mission center [15] connecting first responders, apps, search-and-rescue dogs, a 6-feet-tall humanoid, robots, drones, and autonomous aircraft and ground vehicles. The command and control center optimizes the available resources to serve every incoming request and generates an action plan for the mission (see Figure 7.2). The WiFi network is created on the fly by drones equipped with antennas. In addition, the autonomous rotorcrafts, planes, and ground vehicles are simulated with Simulink® [15] and visualized in a 3D environment (e.g., Google Earth™ [16]) to unlock the ability to observe the operations on a mass scale (see Figure 7.3).

7.3.2 Architecture for Smart Emergency Response System

The components of SERS architecture are presented in Figure 7.4. The mission command and control center in the middle of the figure is the computational brain of the system. Every time a help request from the Android™-based smartphone application [17, 18] comes in, a fleet of robots, dogs, and autonomous vehicles is sent to the field for operation purposes.

The fleet consists of the following hardware elements (illustrated on the left side of Figure 7.4):

- WiFi drones equipped with antennas to set up the WiFi network [19, 20]
- Biobots (i.e., dogs equipped with sensors such as, cameras or gas detectors) to sense and monitor the situation [21]
- KUKA mobile robotic arm for performing difficult field activities, such as gas leak removal [22]
- Haptic device for tele-robotic remote operations [23]
- ATLAS humanoid for performing heavy lifting operations and reaching areas too dangerous for a human [24]
- Fleet of UAVs (i.e., drones and fixed wings) and ground vehicles simulated and shown in a virtual 3D environment [25–27]

Figure 7.2 Illustrative presentation of the optimization process on a geographic map. (Source: Courtesy of MathWorks.com.)

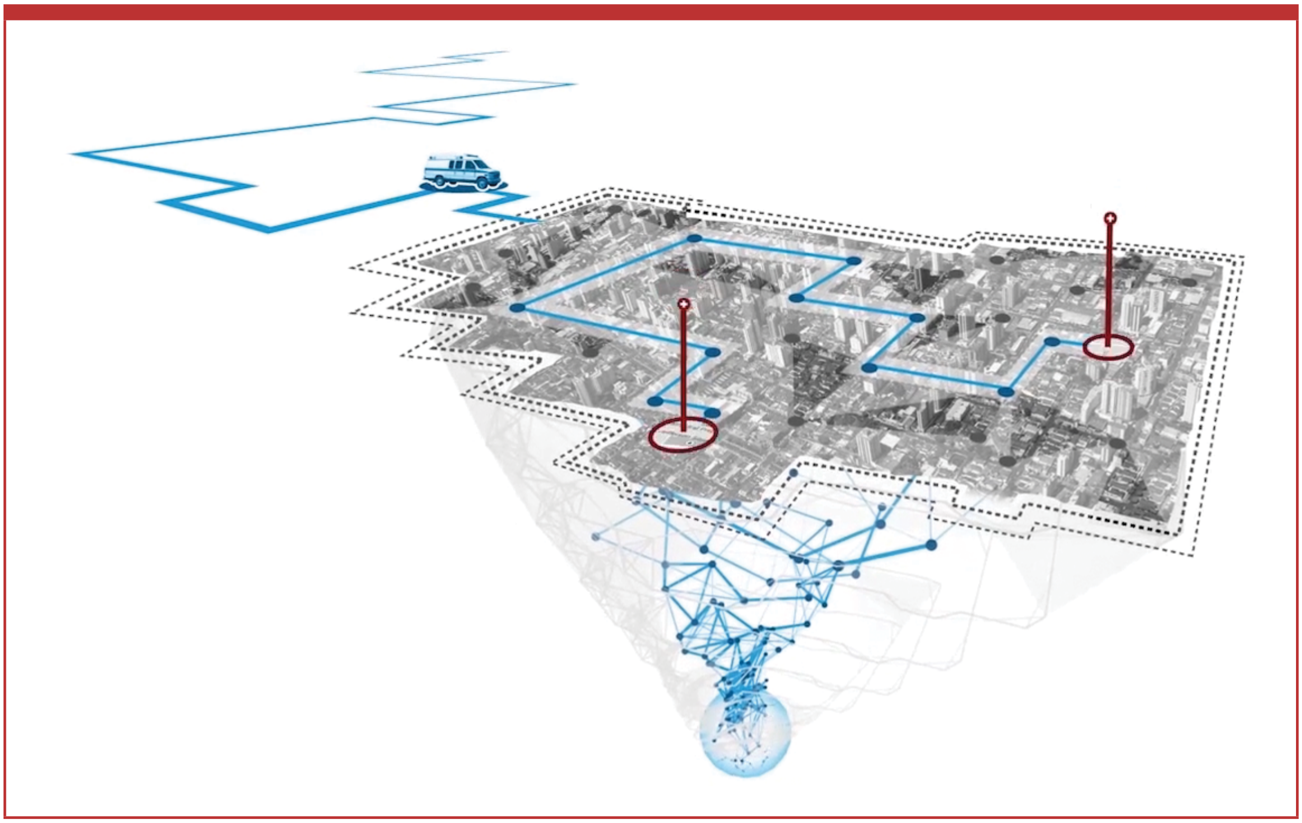


Figure 7.3 Illustrative presentation of the mission simulation. (Source: Courtesy of MathWorks.com.)

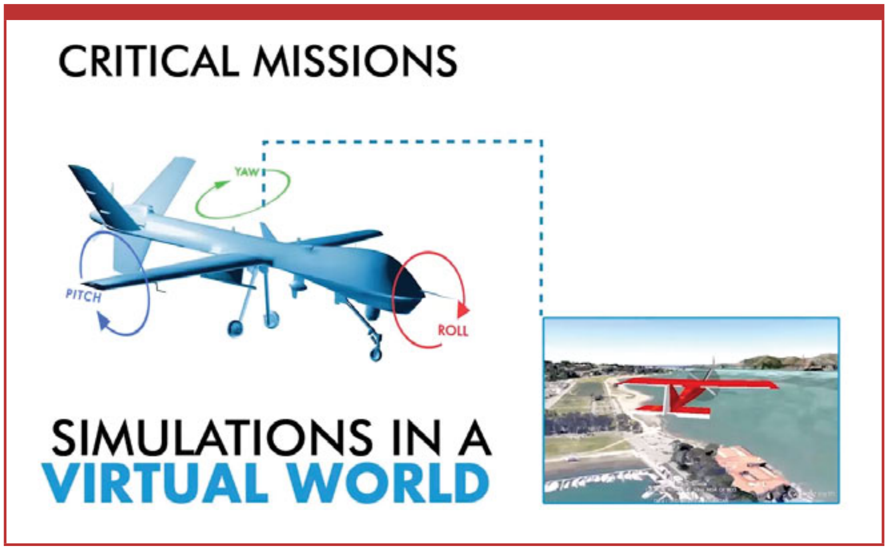
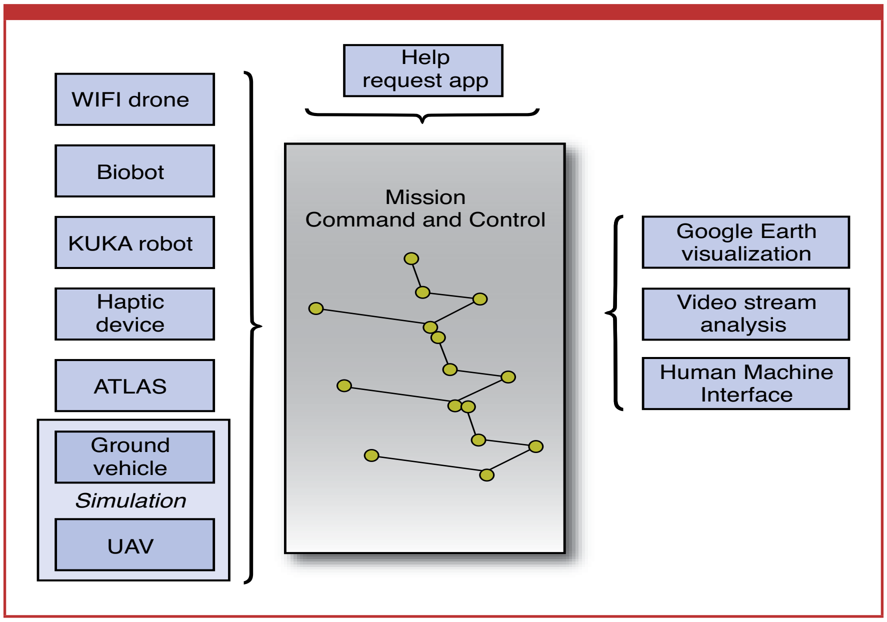


Figure 7.4 SERS system architecture.



In addition, SERS consists of the following human-machine interfaces depicted on the right side of Figure 7.4:

- Simulink to Google Earth interface for visualization of the simulated field operations
- A component for the video stream analysis of the cameras placed on the drones (e.g., AR.Drone [28]) to perform real-time face detection of the survivors in the field
- Wearable computing for observing and manipulating certain elements of SERS

The necessary communication infrastructure is provided by an opportunistic network based on the app [17] that relays messages between mobile devices, as well as an ad hoc WiFi network set up by autonomous drones equipped with directional antennas to increase reach.

The communication between the components is realized using User Datagram Protocol (UDP), Transmission Control Protocol (TCP), and serial connections, depending on the integrated component.

The complexity of the system integration is embraced by the software logic that is implemented in MATLAB. The **simulation** of the dynamic systems (e.g., ground vehicle) included in SERS is implemented in Simulink and other blocksets.

A more detailed architecture of SERS, including the underlying implementation and hardware details is presented in Figure 7.5.

The SERS software is divided into six logical components as shown in Figure 7.6. In particular, it consists of components such as:

- Simulation and visualization
- User interface
- Optimization of the resources
- Hardware integration
- Requests
- Helpers

SERS software is built based on an object-oriented approach [29]. That is, each logical component is represented by a number of classes and their methods.

Figure 7.5 SERS system architecture — detailed view.

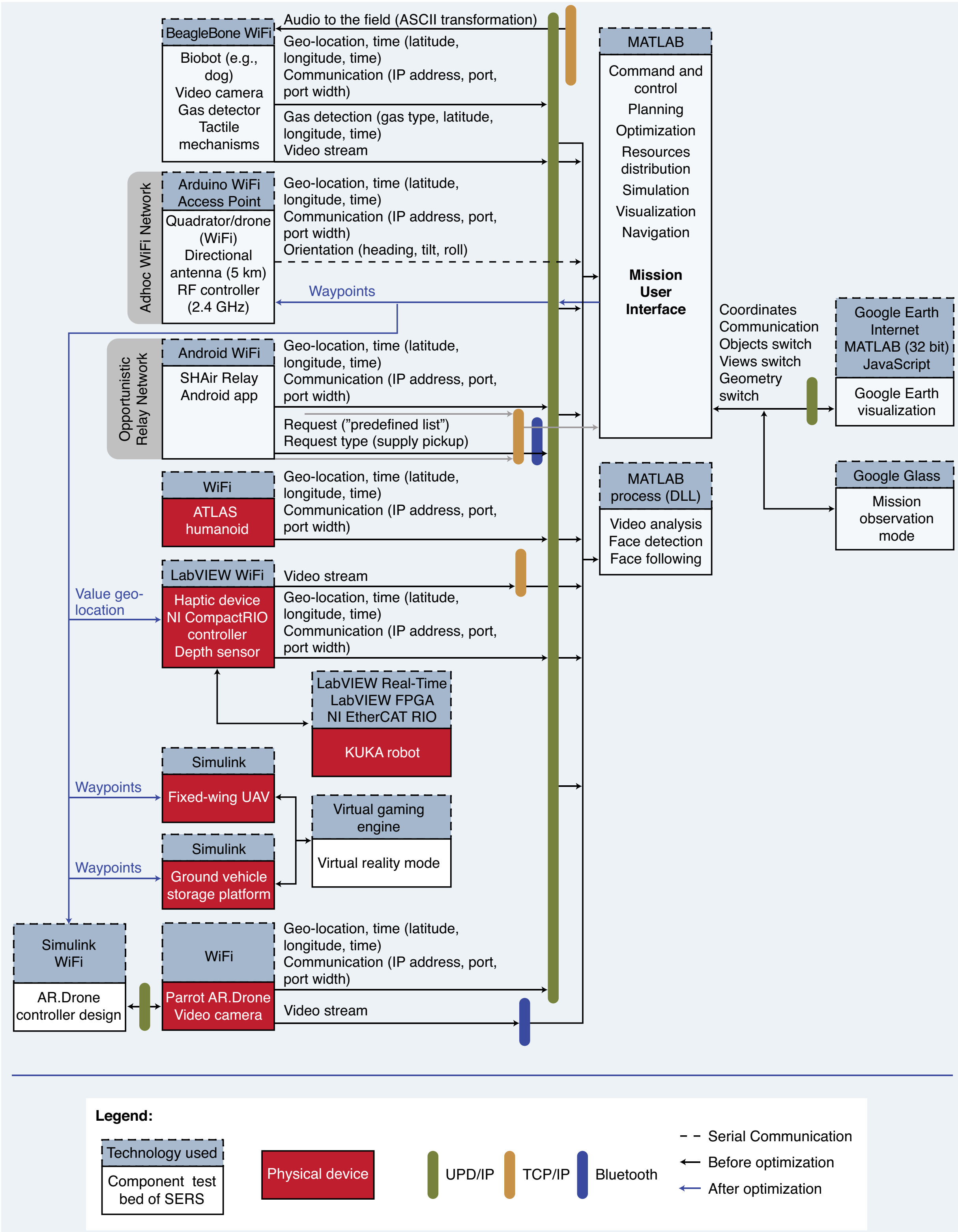
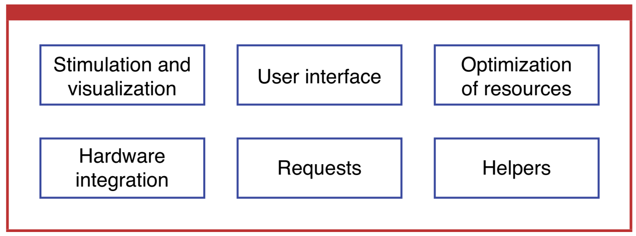


Figure 7.6 SERS software architecture.



7.3.3 Model Based-Design and Its Role in Smart Emergency Response System

The SERS concept illustrates how to arrange for a more effective disaster response. The paradigm of CPS unlocks the potential for hardware and software collaboration. A seamless interoperability between hardware and software components is enabled with model-based design (MBD), which MathWorks typically advocates for embedded systems development. Also, the rapid prototyping of components is supported by simulation techniques. Most importantly, an open design makes the accessibility, processing of data, and computation meaningful for the rescue operations directly in the field, which holds the promise that technology will change the game in the emergency response efforts.

A prototypical implementation of SERS is available on GitHub, a platform for collaborative software development [30].

7.3.4 State of the Art in Related Multidisciplinary Fields

In the following paragraphs, research related to smart emergency response is presented. It illustrates the opportunities and obstacles to achieve the advances described in the previous section.

Fire moves quickly. For example, wildfires occur each year and destroy thousands of acres in a few hours. Wind can push the fire in unexpected directions. Thus, only the proper technology can encompass the complexity and help fire fighters in resolving the disastrous scenarios [31].

Technical solutions exist; however, they are still isolated and not scaled up in terms of deployment. Multiple initiatives are still being researched and developed. For example the WIFIRE project [32] at the University of California San Diego capitalizes on the information from weather sensors and satellite images to predict where wildfires are moving, all in real time. The images and data create a network of real-time wildfire information that then unlocks the potential to forecast where the fire will move while it is burning.

Along another dimension, the use of social media for situational awareness during emergencies has been studied extensively in other work [33]. Community participation in common goal-driven initiatives has been researched by others as well [34, 35]. For example, evidence is provided that collective intelligence outpaces the intelligence of an individual contributor [34].

Specific to unmanned autonomous vehicles (UAV), a recently launched humanitarian UAV network bridges humanitarian and UAV communities internationally [36]. The objectives of this community include providing coordination support, facilitating information sharing, enabling safe UAV operations, and establishing clear standards for humanitarian use [36].

In this spirit, bringing simulation to the masses constitutes a tremendous opportunity to keep the society, and not only first responders, informed about the operations in the field [25]. Further, using simulation as a mass-scale information provider opens up the area of **actionable intelligence**. That is, following the knowledge that can be retrieved from the computational space, the doers and makers may be given the tools to actually act and improve the field operations whenever such an improvement is required and desired.

Capitalizing on the existing and broadly-used platforms such as Google Earth allow for a high-level understanding of the realistic scenarios. Communication between the stakeholders becomes more efficient.

Currently, much attention in robotics is directed to humanoids. These are being developed by multiple organizations, such as Honda [37], and extended through the DARPA challenge [38].

Researchers are making tremendous progress in engineering systems such as communication devices, cars, and airplanes applying MBD methods. They use executable modeling and numerical computation for creating behavioral predictions in a virtual world of simulations. These activities ultimately allow for auto-generation of millions of lines of code out of models and deploy this code on a physical machine. For example, the Chevrolet Volt was created with such methods in just 29 months [39] in full compliance with legislation, whereas a typical manual process would take about 5 years.

7.4 Potential Action

While the technology advances, business models for humanitarian actions are under development and not yet quite clear. The incentives to empower the execution of the Smart Fire Fighting roadmap come rather from other technical areas and conveniently contribute to the emergency response solutions. To achieve optimum impact, proper initiatives have to be revitalized. It is a difficult endeavor in the world of capitalism. However, looking to the future, there is hope. For example, the U.S. government announced in June 2014 at least three U.S. national-level initiatives that are strictly related to smart emergency response.

7.4.1 National Institute of Standards and Technology

The National Institute of Standards and Technology (NIST) has posted a Federal Funding Opportunity (FFO) for a new research Center of Excellence to work with academia and industry on issues in community disaster resilience. NIST will select an awardee based on a merit competition to establish the center, which will be funded at up to $4 million a year for five years (total up to $20 million). NIST Centers of Excellence are meant to provide multidisciplinary research centers where experts from academia, industry, and NIST can work together on specific high-priority research topics. The center will work on developing integrated, systems-based computational models to assess community infrastructure resilience and guide community-level resilience investment decisions. The proposed center would also develop a data management infrastructure, as well as tools and best practices to improve the collection of disaster and resilience data.

7.4.2 Department of Homeland Security

The Department of Homeland Security (DHS) Office of University Programs (OUP), within the Science and Technology Directorate, is releasing a Funding Opportunity Announcement (FOA) for a new DHS Critical Infrastructure and Resilience Center of Excellence (CIRC) Cooperative Agreement. The Center Lead institution will fund partnering organizations through sub-awards. For applicants interested in only submitting a partner proposal, OUP is also posting a separate FOA for eligible applicants to submit single project proposals for consideration as a partner to this Center of Excellence (COE). Funding for the center will total $20 million over five years and DHS will make one award.

7.4.3 SmartAmerica/Global Cities Challenge 2014–2015

Current deployments of CPS/IoT in smart cities/communities are fragmented, lacking interoperability and standards. As a result, many smart community deployments are isolated and do not enjoy the economy of scale. Many CPS/IoT innovators already have technologies (i.e., building blocks) and their impact can be maximized by fostering collaboration among the innovators to create interconnected solutions to provide tangible benefits to the end users. The SmartAmerica/Global Cities Challenge is aiming to address the issue by establishing and demonstrating a measurable, scalable, and repeatable model for incubation and deployment of CPS/IoT technologies in smart communities/cities to accomplish improved efficiency and productivity, create new business opportunities, and create affordable and sustainable living environments to enhance the quality of life. All the teams in SmartAmerica Round One will be invited to participate in the Global City Teams Challenge, as will new participants from around the world. SERS submission to the challenge is available online [24] and described in detail in Simon et al. [40], including a vision on its application in Mosterman et al. [41] and Zander et al. [42].

US Ignite and the National Institute of Standards and Technology have teamed-up with partner organizations — the National Science Foundation, The Departments of Transportation and Health and Human Services, ARM Holdings, Cisco, Extreme Networks, IBM, Intel, Juniper Networks, and Qualcomm — to create the Global City Teams Challenge, an initiative designed to advance the deployment of Internet of Things technologies within a smart city environment.

7.4.4 Smart Emergency Response System in Summary

The SERS concept illustrates how to arrange for a more efficient and effective disaster response. The CPS paradigm unlocks the potential for hardware and software as collaborating modalities. Integrated interoperability between hardware and software components at various levels of abstraction is enabled with Model-Based Design. Also, the rapid prototyping of components and integration into the system under design is supported by simulation technology. Most importantly, a design on an open and trusted platform makes the accessibility, processing of data, and computation meaningful for rescue operations directly in the field, which holds the promise that technology forces will dramatically change the equation in emergency response efforts.

7.5 Acknowledgments

Some of the results presented in this chapter were developed as a response to the SmartAmerica Challenge 2013–2014, a United States government initiative, and were presented at the White House in June 2014. In particular, the Smart Emergency Response System (SERS) prototype has been created by a team of nine organizations led by MathWorks. SERS team member organizations include BluHaptics, Boeing, Massachusetts Institute of Technology, MathWorks, National Instruments, North Carolina State University, University of North Texas, University of Washington, and Worcester Polytechnic Institute (WPI). Thus, a sincerest gratitude is expressed to each and every team member organization and to all contributors. Special acknowledgements are directed to Dr. Pieter J. Mosterman of MathWorks and Prof. Dr. Taskin Padir of WPI.

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CHAPTER 8

Real-Time Data Analytics

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Abstract

Analyses and action guided by data flowing through well-established and ad hoc local and global networks can be considered the "smart," in "Smart Fire Fighting." Valuable real-time data and communications at and from the scene of the fire are augmented by data that fire department personnel routinely collect in their prioritized visits to different parts of their jurisdiction. The real-time data and communications rely on smoke, light, heat sensors, and communication networks. This chapter begins with a fire tragedy from New York City, then discusses the role of FDNY's FireCast program that supports the agency's efforts in Smart Fire Fighting. The role of research in Smart Fire Fighting is examined, with an emphasis on early detection using smart sensors and rapid communication.

Keywords

data analytics
computer-based simulations
decision theory

8.1 Case Study Description of Topic Area

At 3:30 p.m. on August 18, 2007, a fire broke out at the Deutsche Bank Building at 130 Liberty Street, a once towering skyscraper in downtown Manhattan. The building had been fatally damaged during the terrorist attacks on September 11, 2001, and it had since been undergoing hazardous material abatement and demolition. The New York City Fire Department (FDNY) responded, unaware of manifold obstacles that would inhibit fire suppression efforts as fire fighters performed floor operations. As a result of asbestos abatement efforts, containment walls had been erected that blocked egress routes. Furthermore, demolition had knocked out the standpipe in the basement, preventing water from reaching the 14th floor, where the fire was located. Fire fighters trapped due to blocked egress and other deactivated safety measures transmitted maydays. FDNY could not use standpipes to supply water, and the situation quickly grew to a seven-alarm fire. New York City fire fighters Joseph Graffagnino and Robert Beddia succumbed to their injuries, and approximately one hundred other fire fighters were injured battling the blaze.

In addition to criminal investigations, policy bodies, including the NYC Mayor's Office and a three-agency committee, launched comprehensive process and administrative investigations, which determined that the lack of information sharing and communication between oversight agencies led to an unprepared response. Among the policy solutions that were formulated, FDNY comprehensively re-imagined its fire preparedness strategy to incorporate a new risk-based inspection approach to mitigate future tragedies. Multiple aspects of this approach are depicted in Figures 8.1, 8.2, and 8.3.

For a building under demolition in New York City, inspections were required at specific time intervals by three of the cities departments: FDNY, Department of Buildings, and Department of Environmental Protection. Yet records showed that inspections were not being done at the required time intervals, and worse, there was no coordination among the

Figure 8.1 Detail 1 of FDNY's risk-based preparedness and fire prevention efforts. (Source: Courtesy of FDNY Analytics Unit.)

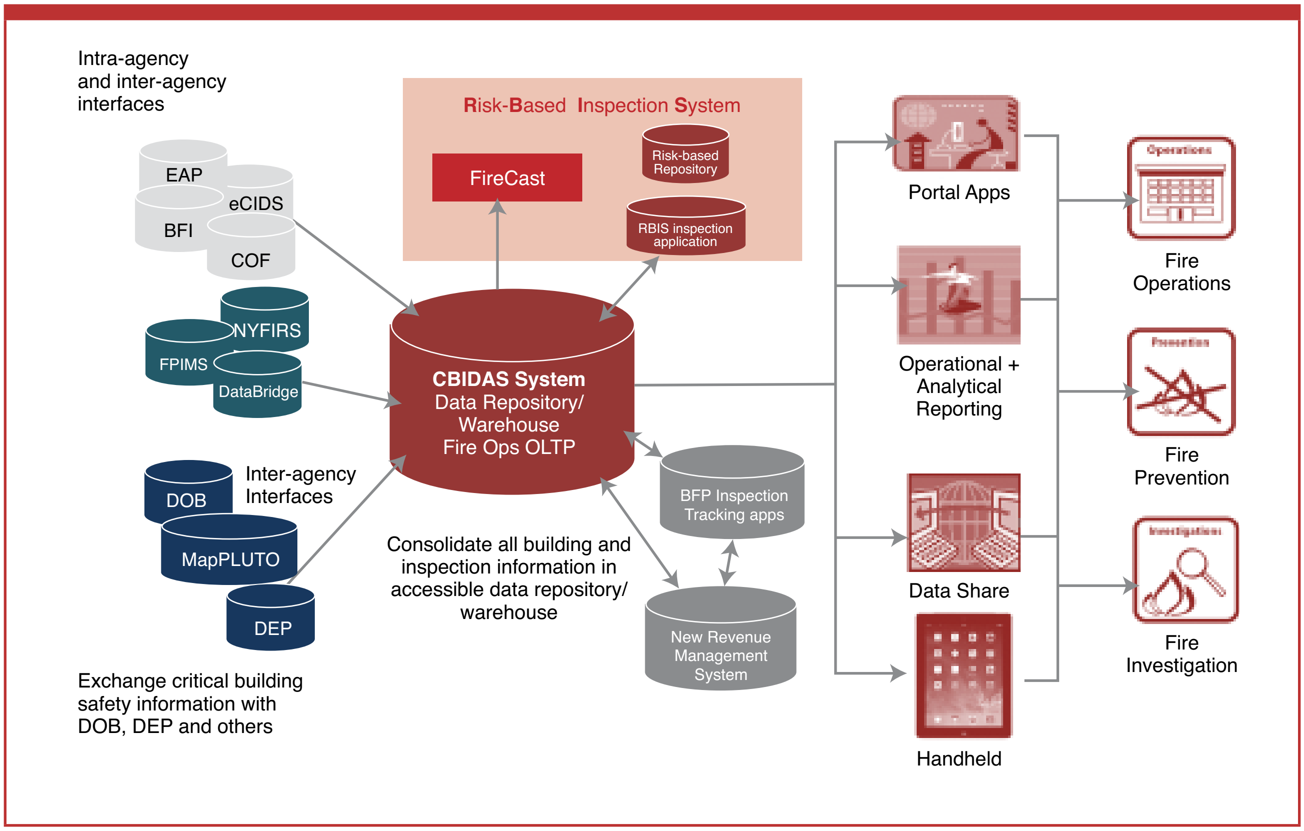


Figure 8.2 Detail 2 of FDNY's risk-based preparedness and fire prevention efforts. (Source: Courtesy of FDNY Analytics Unit.)

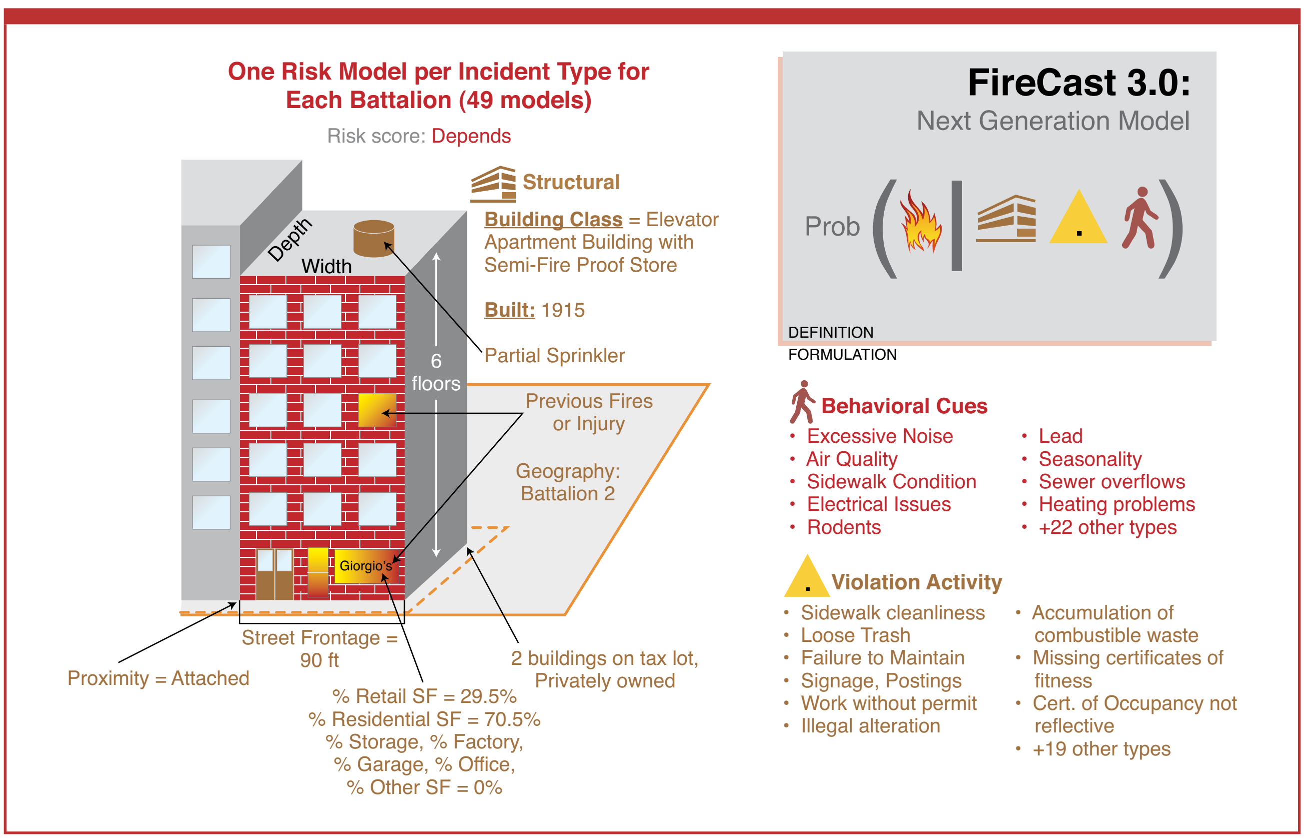
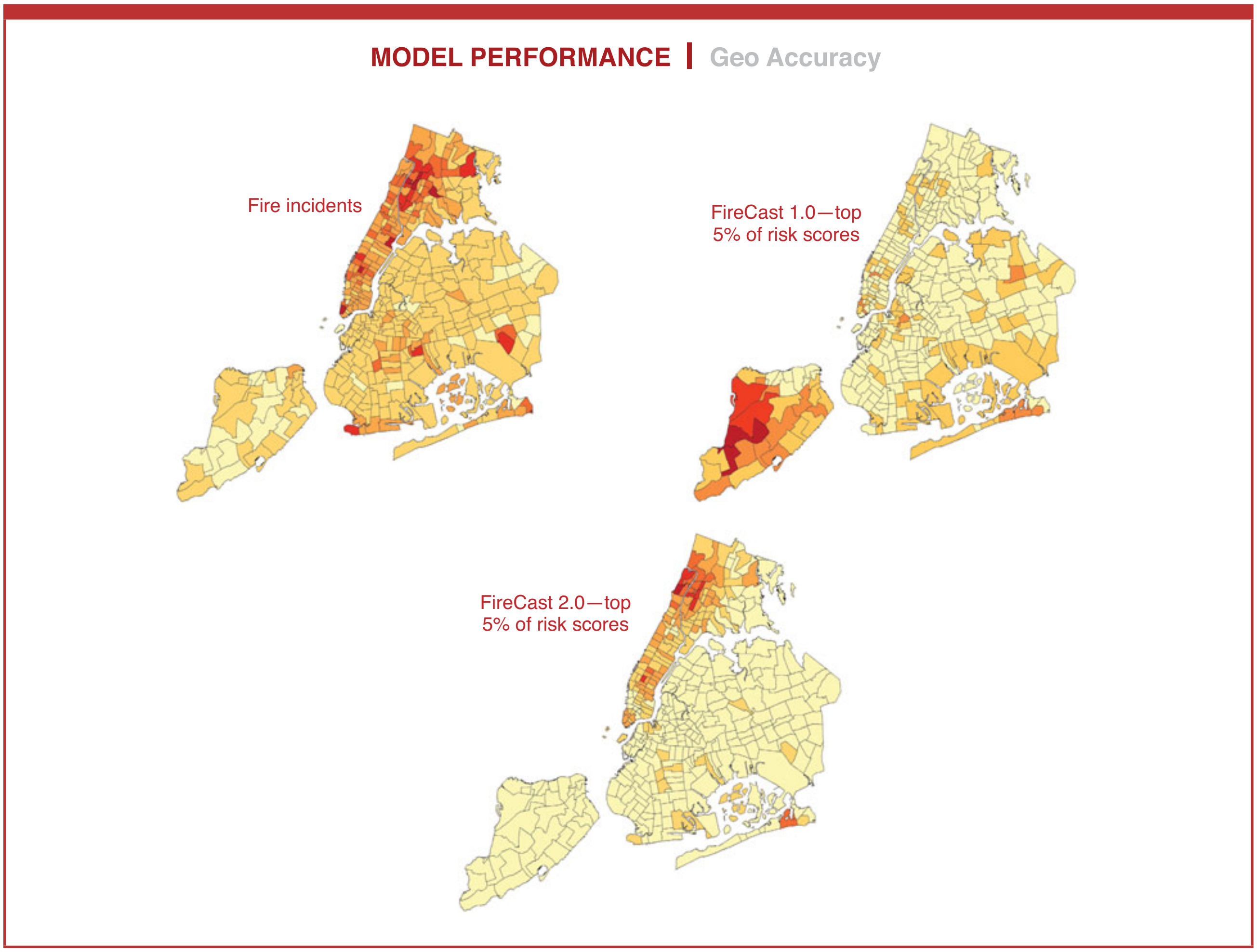


Figure 8.3 Detail 3 of FDNY's risk-based preparedness and fire prevention efforts. (Source: Courtesy of FDNY Analytics Unit.)



responsible departments for sake of effectiveness or efficiencies. Long-discussed changes at city hall were set into motion in the aftermath of the Deutsche Bank fire. The Department of Buildings and the Department of Environmental Protection were ordered to begin automatically sharing all new building and inspection information they gathered with FDNY. Most importantly, the mayor signed an executive order creating a citywide data-sharing platform that allowed agencies and even the general public to view and update the vast amount of data collected by city agencies [1].

The Deutsche Bank Fire is just one example of many tragic fire incidents that have raised the need for the advancement of data sciences in the fire service, namely for preparedness and prevention, situational awareness, and decision making. The data required, both physical sensor and social in nature, might be extracted, transformed, and loaded for sophisticated and impactful data analysis to enhance the modern fire service's ability to prevent, prepare, and respond to incidents. The analysis of data (i.e., **data analytics**) has been clearly identified as a critical tool for preventing future tragic events like the Deutsche Bank Fire.

8.2 Risk-Based Preparedness and Fire Prevention Efforts

The current state of data analysis covers a wide range, from computationally intensive fire simulation methods to large-scale data mining operations that require significant computational resources, and thus do not lend themselves to field operations or real-time application. The day is not too distant when this application will be realized. However, in this chapter, the application of current pre- and post-fire computer modeling is not addressed.

In focusing on risk-based preparedness and fire prevention efforts, FDNY's Risk-Based Inspection System (RBIS) is a technology-driven policy response to arm fire units with critical field intelligence to enhance preparedness and prevention. The system was designed to schedule and track inspections of varying scope so that responding companies can mitigate adverse conditions in buildings as well as visualize and understand risks when responding. In order to effectively schedule inspections based on risk, RBIS is powered by the FireCast Predictive Risk Engine, an in-house developed machine-learning program that disseminates massive amounts of information to identify buildings with the greatest risk of fire ignition. On July 18, 2013, FireCast 2.0 was launched using National Fire Incident Reporting System (NFIRS) fire incident records and 13 types of risk factors, including geographic and structural characteristics. This was a major step toward a dynamic risk-based management system. While the risk scores are updated daily to reflect changes in the underlying data, the model is maintained and recalibrated on an annual basis. Statistically, the model has fairly high targeting accuracy with AUC of 0.89. [AUC is the area under the curve as derived from the receiving-operating characteristic (ROC) curve.] Operationally, FDNY relies on the pre-arrival coverage rate (PACR) statistic to estimate efficacy between model targeting and operational follow-through. The PACR is defined as the proportion of buildings that experienced a fire and that had been inspected within 90 days before the incident. FireCast 2.0 is currently rated at 16.5 percent, whereas FireCast 1.0, which was based on assumptions rather than data, is rated at 1.9 percent. Thus, statistical algorithms have improved performance by eightfold.

FireCast 3.0, the latest addition in the FireCast pedigree, is a big data initiative that combines FDNY's computer-aided dispatch records and 7,500 risk factors such as social data (e.g., complaints and data from the 3-1-1 non-emergency phone reporting system), operations and enforcement data (e.g., violations from multiple agencies), and physical data (e.g., building and land-use characteristics) — all of which are collected from dozens of city agencies. To retain accuracy and applicability to daily operations, FireCast 3.0 is designed as a fully machine-learning algorithm that examines the signal-to-noise ratio and discriminate power to identify statistical significant candidate risk factors, then develops battalion-specific fire risk models to prioritize buildings using generalized linear models (GLM). This means that the new risk model will readjust itself to activities in the field, meaning that the risk factors may change from day-to-day. If new risk trends emerge in the dynamic complaint and violations data, the risk algorithm will automatically detect those new patterns by looking for evidence to statistically link it to fires, then incorporate it into the risk score. The algorithmic design was developed to be flexible to allow for estimation method adjustments to incorporate more complex and robust statistical approaches such as ensemble methods, random forests, support vector machines, artificial neural networks, and other data mining methods.

Many fire departments across the country are working toward similar programs. A FireCast 2.0–based approach is more likely to be broadly deployed than a FireCast 3.0–based approach based on the current availability of digital data. Cities that currently have robust 3-1-1 systems or public service request systems are strong candidates for this approach.

8.3 Summary of Perceived Future Trends

8.3.1 Computer-Based Simulation

Numerical simulations are widely used in the CPS community, simulating the transport of smoke and fire spread, evacuation patterns, and structural resilience with respect to fire loads. However, these methods are not without limitations, because such simulations of fire conditions are dependent on unknown or uncertain parameters that are key initializing assumptions. Thus, results are contingent on the assumed values of uncertain parameters. It is logical, then, that incorporation of data assimilation (DA) offers a prospect of refining uncertain parameters with real-time inputs. DA may increase the accuracy and fidelity of **computer-based simulations** by using data captured through sensor technologies. For example, there are significant barriers to accurate prediction, especially given unknowns regarding fire complexity and human behavior.

Several fire research groups, for both wildland and building fire applications, have explored the idea of data assimilation recently. Data-driven fast physics fire models will be developed and evaluated to accomplish the following tasks:

1. Forecast fire spread and fire plume dynamics (forest test bed).
2. Detect incipient fires and optimize the response to a growing fire in terms of providing safe egress, assisting first responders, and activating building systems (e.g., fire suppression systems and HVAC systems; building and transportation test beds).
3. Monitor the health of a structure and/or an engineering system (building and transportation test beds) supported by fire fundamental experiments.

To support the use of these models for decision making, parameter inference tools will be used to produce stochastic models to assimilate the sensor data. Compact mathematical representations to model under-sampled probability distributions and computationally efficient models for uncertainty propagation will be developed.

8.3.2 Decision Theory

Decision theory will be applied to develop a framework that does the following:

1. Identifies the information used by decision makers in the system test bed environments
2. Characterizes the sources and properties of uncertainty in the sensor data, models, and networks
3. Communicates information relevant to the alternative strategies that a decision manager is considering

The decision theory approach directly addresses the human behavior barrier, and this has been addressed by an initiative referred to as the Smart Network Infrastructure for Fire Resilience (SNIFFR) [2]. The focus will be on decision making incident commanders (ICs) engaged in fighting forest, building, or transportation fires.

These ICs are responsible for deploying resources to mitigate the fire and evacuating civilians from the fire threat. Research on naturalistic decision making (NDM) and decision analysis will be used, considering decision processes under stress and use of sensor data and other information to increase situation awareness and inform options analysis. Expert ICs from the three test bed environments will be surveyed to encapsulate their information gathering, assessment, and decision-making strategies into mathematical models, through which the type of information that most affects their decisions can be identified, along with the sensitivity of decisions to that information. In the SNIFFR system, sensors, sensor networks, models, and communication networks provide information to increase situation awareness. Since sensor signals do not perfectly map to the state of the environment, there is noise in networked signals, and models contain bias and model parameter uncertainty. One can consider that the nominal outputs are enveloped in uncertainty. To address that issue, the overarching objective of the decision theory thrust is to best synthesize the data, network characteristics, and models to reliably communicate the system state given the state of uncertainty across all planes. The decision theory has been integrated throughout the thrust area and test bed discussions.

8.3.3 Prevention and Preparedness

Risk-based approaches may be accessible by fire departments across the country provided that basic data requirements are met. The basic outcome data are based on the digital CAD fire incident data, which are available through most 9-1-1 call centers, or NFIRS data for serious fires. These outcomes are the targets against which the risk factors and risk predictors are tuned. The nature of predictors may vary, but must contain geo-location and date-time information to allow for correlative analysis. For example, a few dozen American cities have launched 3-1-1 systems that divert routine, non-urgent, community concerns to a call center.

In practice, a team comprised of a computer scientist and a statistician may be able to develop a basic risk prioritization application that is trained on data. Through rapid and iterative prototyping, a data science team may use open source statistical computing such as R and Python to uncover correlations between CAD data and other geo-located data that may provide some predictive signal. Candidate risk factors, as identified through exploratory data analysis, can be used to train a binary classification model (e.g., random forests, logistic generalized linear models) that relies upon underlying data to prioritize lists of buildings or flag high risk buildings. Assuming predictive models are sufficiently accurate, models should be iteratively field tested in order to constantly refine the algorithm. To track the impact, targeting accuracy should be benchmarked against some pre-existing baseline. As the data-driven approach matures, a simple data collection and targeting application should be constructed. Basic and ad hoc applications can be hosted using user-friendly cloud-based services such as Google Drive, and more advanced applications may require full suite hosting services such as Amazon Web Services or Heroku. The fire service, while engaged in prevention, is still a response-driven public service focused on tangible evidence. For many, data science is abstract. Thus, adoption is dependent on the ability of the CPS and technologist community to contextualize and characterize data-driven applications in ways that are relevant and accessible to fire operations.

8.3.4 User Experience

While the science may yield accurate and precise insight, there is an inherent need to develop an interface between science and practice so as to ensure that users may maximally benefit from the predictive resources. Thus, particular emphasis should be placed on user experience and decision theory to identify key information elements generated from sensor and human sources that are utilities for fireground decision makers. Future developers should consider the following:

- As is common in user experience research in fields such as marketing, A/B testing and factorial testing should be conducted on predictive utility outputs so as to ensure proper interpretation.
- In the field of geographic information systems, research has led to improvements in the use of colors in cartography, which has vastly changed the manner in which data are presented and understood.
- Qualitative process tracing of past disasters (to better understand the relevant factors), agent based modeling (to predict crowd and group behaviors in safe virtual environments), and field experiments of the technology. Evacuation rates and speed from residents, along with response time and appropriate tactics from first responders, will be used as core performance metrics. Once these metrics surpass those of current technologies, the SNIFFR system will be ready.

8.4 References

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CHAPTER 9

Fire Service Data User Applications — Pre-Emergency and Post-Event

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Keywords

pre-emergency
post-event
inspection
enforcement
pre-planning
training
education
investigation

Abstract

Preparation for safely and effectively managing a fire either in the urban, wildland-urban interface, or wildland environment begins long before the actual incident. Fire fighters can be more effective and safe if they have the ability to access accurate, up-to-date, comprehensive information about the fire, its location, the burning environment, hazards, and resources on the fire site. However, we exist in an environment where we are constantly inundated by information. In this age of digital information overload, first responders require tools to assist in displaying the information in formats that are understandable and usable given complex and narrow decision space. Thus, effective management of fire incidents requires not only tools to process and display data, but also preparation both before and after fire events to collect and archive data prior to a particular incident.

When preparing for and traveling to and from fire incidents, first responders must make many decisions quickly. Decision effectiveness can be improved through the access and use of user applications that provide detailed and up-to-date information about the incident, including location, threats to resources and humans, the emergency resources available, and the surrounding environmental conditions. Systems that provide this information can assist responders in determining the best available actions to protect human life and reduce threats and damage to resources. Fire service data user applications are improved when more detailed and accurate information is available. Critical information is developed and provided by inspectors and enforcers, through training and education, and from fire investigations. The required information can only be obtained from data collected prior to the event, or after other similar events have occurred in the past. Similarly, accurate assessment of the effectiveness of equipment, tactics, and resources is best evaluated when complete information about incident characteristics, resource capabilities, and location characteristics is observed, recorded, and archived.

It is readily recognized that "turning data into information is neither simple nor easy. It requires some knowledge of the tools and techniques used for this purpose. Historically, the fire service has had few of these tools at its disposal and none of them has been designed with the fire service in mind" [1]. This chapter discusses data needs and sources for improving a fire fighter's situational awareness when traveling to or working on a specific fire incident.

9.1 Description of Topic Area

In 2010, seven career fire fighters were injured on a fire at a large commercial facility [2]. Contributing factors to the accident were unknown property contents and unknown presence of combustible materials. Key findings in the post-incident report were the recommendation that pre-incident plans be regularly updated and made available to responding fire crews. Pre-incident planning is critical to effective and safe incident management. Planning should include not only collection of infrastructure information, but also occupancy details, site and property details, special hazards, unique weather conditions, traffic aspects including optimum approach routes, and so forth.

Today, fire management organizations exist in an environment of data overload. Indeed part of this is due to the changing roles of the fire service, often fire agencies find their responsibilities expanding into EMS, hazmat, **inspections**, **investigations**, prevention, and community **education**. Given these changing roles and increased responsibilities, the sheer quantity of data makes its effective use impossible. As the information age continues to advance, interest from fire management organizations in accessing real-time, accurate, data has also increased.

By themselves data are of little use; however, when simple facts such as building location, water source location, water source supply rate, hazardous chemical presence and quantity are organized into a meaningful structure, they become information. When meaningful information is organized on a contextual basis it can be considered knowledge. The conversion of data to information is neither simple, easy, nor standardized. It requires specialized knowledge, tools, skills, and techniques. However, as data are converted to information and that information is presented in a format that is easily accessible and understandable, it becomes knowledge that can inform and guide decision selection [3]. When decisions about resource allocation and tactics improve, society as a whole benefits. Thus the utility of up-to-date, accurate, and temporally and spatially explicit data can increase the ability of fire managers and crews to safely and effectively manage fires.

Preparation for effectively managing a fire either in the wildland-urban interface (WUI) or in an urban area begins long before the actual incident. With the advent of the information age, data is all around us. The sheer magnitude of it is increasing exponentially, and our capability to access it is also increasing. Given present and emerging technology capabilities, it is entirely conceivable that fire fighters could have access to significantly more information than they have had in the past. However, as with many areas of society, knowledge is only as good as the data used to develop it. The capability to access detailed data is a two-edged sword. On the positive side, it can assist fire managers and crews to accomplish their duties more safely and effectively. On the negative side, the sheer volume of data can overwhelm the user and the system that is processing the data.

Typically, fire fighters have been required to make decisions regarding tactics with limited information prior to arrival at the scene. This has limited decision effectiveness. When preparing for and traveling to fire incidents, first responders must make many decisions quickly. Decision effectiveness can be improved when made with detailed and up-to-date information about the incident, including location, threats to resources and humans, the emergency resources available, and the surrounding property and environmental conditions. Systems that provide this information either before deploying or while in route can assist responders in determining the best of available actions to protect human life and reduce threat and damage to resources. The NFPA has developed a comprehensive guide to pre-incident planning (NFPA 1620, *Standard for Pre-Incident Planning* [4]) that provides detailed information, forms, and definitions.

Smart Fire Fighting (SFF) implies that data is translated into knowledge, which leads to improved effectiveness of fire fighters. Implementation of this knowledge can occur through cyber-physical systems (CPS). CPS provides fire fighters with the capability to obtain and use data to more effectively and safely accomplish their objectives. However, as with the mountains of data that are available for processing, the implementation of data collection, the translation of data into information, and communication of information to increase the knowledge of fire fighters are complex technical problems.

As with most aspects of life, increased knowledge translates into increased situational awareness. In the context of high-risk professions like fire fighting, situational awareness can directly affect success and safety of an incident.

Table 9.1 presents a partial summary of data that should be of interest to fire managers. But as described, data is only useful when it has been converted to information that can be accessed and understood by fire fighters. Ideally, the information is most useful when it can used to increase knowledge and situation awareness.

9.2 Literature Review

The U.S. Fire Administration has developed a handbook that attempts to describe various tools and techniques for converting data into useable information and knowledge [1]. It describes a range of statistical techniques within the context of several fire service incidents. It describes how to present data in charts and evaluate trends in data based on various distribution methods. Finally, it describes how to fit data to trends that can be used for forecasting future events.

Table 9.1 Data elements of interest to fire managers.

Data	Conversion to Information	Knowledge Development
Property location	Urban, rural?	Fastest or safest route
Property occupants	Age, special needs	Determine expertise and support systems needed
Property size		Increase situational awareness
Number of floors	Building size	Select best control tactics and equipment
Construction materials		Best suppression methods
Vegetation type, condition, load	Is the property surrounded by green lawn, flammable vegetation, other buildings, etc.? Situational awareness	Optimum management methods
Local water supply location, volume, hydrant or open water	How far to water? Volume of water available? Situational awareness	Optimize management methods
Other infrastructure	Power lines, gas lines, propane tanks, other risk factors	Optimize management methods and equipment
Special hazards	Type, location, amount	Optimize management methods
Condition of infrastructure	Condition of approach roads, presence of electrical or other hazards	Optimize management methods
Proximity of flammable vegetation to structure	Potential for building ignition	Optimize management methods
Presence of decks, wood piles or other flammable debris	Situational awareness	Optimum control methods
Condition of neighboring property	Situational awareness	Optimize control methods
Is the property in cellular coverage	Situational awareness	Optimize control methods
Proximity to high risk locations	How far to areas or structures that can house large number people.	Optimize and rebuild support infrastructure

A recent white paper describes how geographical information systems can serve as the vehicle for collecting, archiving, and presenting data for use by fire personnel [5]. The capability to interpret and display data is essentially unlimited. Clearly this technology must play a role in future efforts to collect, analyze and communicate data.

The question of how to utilize sensor networks to provide data and then convert that data into actionable information is not new. Others have attempted to determine not only the optimum sensors, but also their distribution to provide required data density [6].

Post disaster, the actions that can be taken can have significant benefits for future incidents and personnel. For example, standardization of building hazard marking protocols, procedures, and methods is critical. Work has been completed on this topic [7].

9.3 Current State of the Art

In many cases and locations, data about property condition, water supplies, special concerns such as chemical hazards etc. are not available at all. For others the information is contained on hard copy paper inspection reports. A limited number of locations are collecting data digitally, processing that data and providing fire managers with user selectable summaries. The data collection is not standardized and varies widely from municipality to municipality. In many cases data is not sufficient to develop complete assessments of resources at the specific locations or to develop location specific summaries.

Systems and methods for collecting, archiving, and interpreting data are improving. However, much work is still needed. Advanced military systems have the capability to ingest and process large amounts of data, integrate those data with real-time video imagery, and transmit that imagery and interpreted data to on-the-ground troops. Similar capabilities do not exist in the public sector. However, there are efforts underway at various local, state, and federal agencies to develop systems to address these needs.

The lack of organized systems for collecting and cataloging site specific data is most severe in urban areas of developing nations [8]. However, advances in developed nations can be transferred to other nations.

Some questions relevant to the access, processing, and use of such data are:

1. What is the most critical information?
2. When is information outdated — in other words, how often does it need to be updated?
3. What can be learned after the fact from fire incidents regarding information use?
4. How should the information be archived?
5. In what form is the information most useful to fire fighters?
6. How can the relevant information be obtained?

9.4 Summary of Perceived Future Trends

9.4.1 Pre-Emergency and Post-Event

9.4.1.1 Inspectors and Enforcers

When asked what information would be useful in wildland-urban interface incidents one fire fighter stated "Off the top of my head an app that had the ability to cache maps for offline use, with the ability to toggle on layers of interest. Examples of layers could include weather, fire behavior information, and safety zone dimensions and the information you've listed. The maps would have to be cached to the device when there wireless data available.

What if we could display BEHAVE or other relevant data as you've listed on a handheld moving map? This would help in the tactical planning and size up process. These tools would be an aid to understand the impacts of current observations in the field. There's also a benefit in having something to use before there is actual fire in the area to estimate behavior. These devices can be an aid to situational awareness, but not replace ground truth observations.

There is a hazardous materials app commonly known as WISER [9]. It was developed by an organization called Wireless Information Systems for Emergency Responders. While this app isn't related to wildland fire it takes protection distances from the DOT Emergency response guide and displays them on the device map. Maybe an enhanced IRPG could include some similar features with wildland specific data.

While some information can be obtained from cadastral databases, often specific information about the environment, structure ignitability, and site-specific risks is only available through onsite inspections. Data collection generated by inspections can be critical to **pre-emergency** preparation. However, the spatial detail in the data, as well as the accuracy, are dependent on the individual entering the data and the extent of the inspection. Other factors can be temporal changes in the data due to weather, changing occupation, changes in vegetation, and so forth.

Post-event inspections can provide information and data about how areas, property owners, and communities are attempting to or have mitigated risk. The effectiveness of fire management tactics can be assessed and documented. Information about what worked during a fire event and what did not is critical to development of other community preparation plans.

9.4.2 Pre-Planning

Pre-planning responsibilities fall on both the fire service as well as the property owners. Development of standardized digital data collection systems and databases will facilitate information processing. Ideally the system and data structure will be specified in a process similar to open source software. Such a system could take advantage of social development in a manner like that utilized for crown sourcing.

9.4.2.1 Fire Service

While it would be ideal for each member of the local fire department to go to each property in the city for a “look-see” to know the general layout of each property, unique aspects of the property (e.g., type and location of buildings, building construction materials, type and location of vegetation, location of water supplies, access, exposure to wind and sun, and potential to impact adjoining properties). However, such local surveys are not be realistic in terms of time and energy that may be better suited for other duties. Members of the fire service should at least be knowledgeable of the high hazard properties in the area and have plans on how to approach an incident at these particular locations. If possible, property plans and layouts should be collected to increase the fire service’s knowledge of the area and help them more efficiently develop tactics. Information could also be provided in terms of what standards are being followed in order to provide information in terms of what types of active fire protection systems may be in place, if fire walls are present, the existence of fire pumps, and so forth. Generalized descriptors should be developed that identify the construction and condition of structures. In some cases it would be appropriate to develop standardized risk metrics that are linked to various aspects of the location. For example properties that have a high risk of exposure to toxic chemicals should be flagged and identified, while similar properties with a low likelihood of exposure would merit a different (lower risk) rating.

Ideally, data provided about property use, occupants, water supply, potential chemicals, or other hazards would be time stamped. Data that exceeded a predetermined time since the update would be flagged. When traveling to an incident, fire fighters could adjust tactics depending on the gauged accuracy of data. Newer data would be associated with higher confidence, while older data would be associated with higher risk.

9.4.2.2 Property Owners

Most, if not all, owners and companies within buildings (especially high-hazard occupancies) are required to have emergency plans in the event of an incident. Disclosing these emergency action plans/protocols to the local fire department could increase the efficiency of the plans. Detailed reports should also be available for the fire service in terms of the current hazards in the property, along with the location of emergency shutoffs or other specifications related to hazard controls. A similar approach could encourage owners of vacant properties to develop emergency plans. These could be provided as a few templates that a property owner could review quickly with minimal input of data, such as verification of water sources, potential risks, and emergency contact information.

Again, tactics and strategies could be adjusted in route to the incident based on the quantity and quality of information available for each property.

9.4.3 Training and Education

9.4.3.1 Fire Service

Training and education is a continual process in the fire service. Property use is constantly changing due to weather, changed ownership, vegetation growth, and so forth. Buildings are constantly changing in terms of their structural integrity, as well as the contents that they hold. Being updated on these changes is essential to the safety of the fire service, as they will be able to approach hazards with the most accurate information. Ideally, the best approach would be voluntary data updated by property owners; however, this approach is often unsuccessful. Coordination with tax appraisers or other government organizations could provide much of the needed data. Financial incentives could be provided in the form of tax benefits or expanded zoning options to property owners that meet data update deadlines.

Additional training and education programs would also need to be added related to the implementation of data application so that the fire service could efficiently and effective use beneficial resources.

9.4.3.2 General Public

Emergency plans can be useful sources of data about traffic flow, population statistics, and property risks. The fire service could provide educational programs and outreach to support pre-planning and preparedness to the community. Webinars that are directed to different societal groups, such as primary schools, the elderly, renters, and industrial and commercial occupants, would be useful in providing education about communicating special issues to fire agencies. This could involve changes in property use, changes in construction materials, presence of hazardous materials, and so forth.

9.4.3.3 Social Media

The increased digital connectedness of people and neighborhoods offers opportunities for increasing fire prevention and fire safety awareness in high-impact, low-cost ways. Fire departments can use their social media properties (e.g., Facebook pages or Twitter accounts) as outreach vehicles to the communities they serve for seasonal and emergent fire hazards. For example, posting simple information about how to safely use fireworks before Independence Day and New Year's Eve, and encouraging people to share/retweet, can increase background levels of awareness and attentiveness in a very low-cost way.

Additionally, there is currently an emerging set of online services around connecting neighborhoods, such as Nextdoor.com, which use both web sites and mobile phone apps to provide highly localized and real-time information to homeowners and residents. Such apps/websites can provide very valuable engagement facilities for fire awareness and prevention, ranging from anonymized reporting of potential hazards, to self-reporting about the number of residents and animals at various locations.

Ideally, a national agency or organization could provide a simple "Social Media Playbook" for local fire departments, with some specialization for different kinds of service regions (e.g., urban, rural, WUI). An individual fire department may have limited social media impact, but by following a playbook to reach out, integrate, and collaborate with broader civic news sources and influencers, they may dramatically increase their social media reach without much effort.

9.4.4 Pre-Fire

9.4.4.1 Pre-Incident Information Needs

Pre-incident information includes multiple elements, such as the following:

- Information about hazardous materials in fire area
- Mobile support, providing responders with critical information in the palm of their hand
- Comprehensive decision support, including information about weather, vegetation, and structure risk
- Information about fire intensity, burning direction, and potential for spread
- Guidance on immediate actions necessary to save lives and protect the environment
- Potential unknowns about fire location
- Access to the decision support tools that can provide guidance about fire spread and intensity
- Visualization of fire fighter safety zones on an interactive map
- Mapping of fire size, location, local area, vegetation, and other resources at risk
- Capability for user customization
- Wireless communications to enable data sharing between users.
- Standalone support for additional mobile platforms
- Mobile support, providing first responders critical information where they need it, when they need it
- Information about other resources that could be called upon to respond, including police and ambulance services, wildland fire management resources, local homeowner organizations, public service organizations such as Red Cross and The Salvation Army, and religious organizations

9.4.4.2 Planning

Fire service providers can best plan when they build cooperative relationships with other government entities that are inspecting or otherwise gathering information about property. Carefully coordinated planning with tax assessors, zoning boards, and community development organizations can provide opportunities to update fire service records. Planning is a multifaceted process that covers a range of functions spanning all programs in fire and emergency response organizations. Planning can include the following:

- Capability assessment
- Vulnerability/risk assessment
- Inspections

9.4.4.3 Preparedness

Preparedness is a "continuous cycle of planning, managing, training, equipping, exercising, evaluation, and improving activities." Preparedness can include the following:

- Pre-incident planning
- Resource deployment
- Targeted mitigation
- Training and exercises

9.4.5 Post-Fire

9.4.5.1 Post-Incident

Post-incident information includes multiple elements, such as the following:

- Data needed to evaluate system effectiveness
- Update on system readiness
- Update on resources damaged

There is a tremendous amount of data currently available to the post-incident investigator, and both the quantity and quality will likely increase in the future. Potential systems that could be obvious sources of information are fire alarms and security systems. Some systems record alarm location and time — data that may help investigators piece together what happened. Other less obvious data sources may have value in an investigation, like temperature data recorded by an internet-connected HVAC system thermostat. No matter how good "smart" technology gets, and no matter how quickly our technology can process real-time data, there will always be a need for a post-incident identification and evaluation of a larger body of data recorded by sensors whose data is unknown or unavailable at the time of the incident.

There is a long list of relevant source data that fire investigators are already using on a regular basis, but with some creativity, there are countless other sources that may provide useful information in a post-fire analysis. One expert states that the fire investigation community is regularly running into three main issues relative to such data.

9.4.5.1.1 Recognition Recognizing that there may have been some system or device collecting information at the time of the incident and realizing that data exists in the first place. If we fail to recognize that the data exists, we obviously will be unable to collect and then utilize it in our analyses.

9.4.5.1.2 Obtaining Information Once the investigator is aware that a system or device was collecting information, it can be extraordinarily difficult to obtain such information. With too few resources investigating fires, difficult and time consuming tasks can often completely derail an investigation in lieu of another. Investigators may leave such an investigation "undetermined" and then move on to others that can be completed in a more timely and manageable fashion.

9.4.5.1.3 Normalization of Time Data Every system and device collecting data is typically associated with a different clock, and time differences between clocks can be critical in truly understanding the sequence and timing of events. The analysis of such data then requires normalization of every clock involved. Even the simplest of fire investigations today often involve a dozen or more clocks (e.g., fire dispatch, police dispatch, fire alarm system, security system, employee accountability system, still picture/video/audio recording devices, retail transactions, and cell phones). Normalization of such clock data requires some critical thinking and mathematical skills that may or may not be available to the average investigator.

9.4.5.2 Recovery

Recovery is aimed at restoration. This can include the following:

- Damage assessment/debris removal
- Infrastructure restoration
- Economic and community recovery
- Environmental stability
- Public information
- Analysis and management of recovery efforts

9.4.5.3 Post-Fire Investigators

Inspectors can provide updates to existing information on both the structural integrity of a property/occupancy along with information about the types/number of hazards that are present in a property/occupancy.

Vacant/hazardous property information can be an essential resource for fire fighters. If a vacant and/or hazardous property placard is placed on a property, it could change the fire-fighting tactics to better fit the incident. However, since marking programs are not required in every city and some property owners simply do not put up the placards, this essential safety tactic is going unused. A similar approach could be taken for structures in the wildland-urban interface. Placards using coded information could provide fire fighters with critical information about unique attributes of the property, such as risk of ignition (low, medium, or high), presence of safety zones (yes or no), presence of hazards (e.g., propane tanks and other high risk sources of flammable material), and so forth. If placards are not used, given present technology, is it is entirely possible that fire fighters could have access to GPS-coded information with all of the above attributes in order to mitigate risks.

Compiled data from past fire investigations may provide critical information for a current incident. The fire service as a whole should be able to use key knowledge from investigations to better understand certain incidents, as well as learn from past incidents in order to more effectively attack an incident in the future. Trends in fires, both accidental and intentional, may allow the fire service to prioritize the types of incidents their members receive training in and participate in educational programs about. The time line of events provided in investigative reports may also be substantial in creating a knowledge base of what may happen during any event.

9.4.5.4 Fire Data Analytics and "Big Data"

There is already a huge wealth of data that's been gathered about fire safety, hazard/risk evaluation, and post-incident reports. As new technology enters into service with fire fighters, and as homes become ever more wired (compare with the Internet of Things), there will be even more data available.

Dealing with this flood of "big data" is a new area of technological concern for fire fighters, and generally outside of their traditional areas of expertise. Even insurers and re-insurance companies, which have extremely savvy actuarial and business intelligence systems, are finding themselves challenged by big data.

One possible concept for driving interest and mining valuable information from this giant trove of historical and new data is to promote the field of "fire data analytics," much as "healthcare analytics" has been recently reinvigorated and turned into an area of active research and innovation. A potential way to kick this off would be the creation of a "Fire Data X-Prize" competition, in which many disparate, messy, real-world data sets are made available, and stakeholders in fire prevention and fire fighting set concrete goals for prediction and modeling from this real-world source data. Data scientists would then then be encouraged to engage in collaborations and teams that produce models to compete to see which ones more accurately predict fires, model loss, flag safety issues, and even perhaps predict social behaviors such as "flash mobs" and anomalous gatherings of individuals in unrated structures.

Typically, the biggest hurdle for creating such initiatives is simply inertia and the lack of any single agency or group stepping forward as thought leaders. There is a national movement towards "open government data" which dovetails very nicely with the public safety and code **enforcement** aspects of a fire data analytics, and it is very possible that when such an initiative is launched, there will be many synergistic interactions with federal, state, and local initiatives.

9.4.6 Perceived Priorities for Research

Development of digital forms for collection of pre-event data and post event inspections is critical. However, it is just a critical that capability be developed to archive the data into searchable databases. Ideally, these databases would include the capability to organize the data into information that can then be translated into knowledge by fire services.

What about the idea of having a set of situational "data playbooks" for different general kinds of areas where fire risks follow a common pattern? This could include the following:

- *For WUI:* up-to-date topographic and satellite data, contact info for nearby logistical support (aircraft, HAM radio, even drone operators).
- *For areas near industrial zones:* work with the city to get accurate data on what kinds of hazmat to expect in various properties, accurate information about occupancy, and so forth.
- *For dense urban areas:* work with the city to keep up-to-date information about "high risk" properties (e.g., condemned, multiple code violations). Work with police to keep up-to-date information about "underground" gathering places where fire codes are probably not respected, and do pre-emptive "look see" of such areas to develop a better understanding of what to expect.

9.5 Terminology

CAD – computer aided dispatch
CPS – cyber-physical systems
EMS – emergency medical service
ESE – electronic safety equipment
hazmat – hazardous materials
PPE – personal protective equipment
NFIRS – National Fire Incident Reporting System
NFPA – National Fire Protection Association
N-FORS – National Fire Operations Reporting System
SFF – Smart Fire Fighting
UAV – unmanned aerial vehicles
WUI – wildland-urban interface

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CHAPTER 10

Use of Data During an Emergency Event

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Abstract

In this chapter, the role of data and information gathered and processed from the fireground during an actual fire event is highlighted. The focus here is on the ability to create accurate, timely and actionable situational awareness for all stakeholders ranging from large agencies to an individual and develop a nomenclature for the same. This information comes from heterogeneous sources, including in-situ, mobile, and human sensors. The need for information from multiple entities and infrastructure elements including, but not limited to, buildings, transportation systems, wildland, and special applications (e.g., proximity, technical rescue, hazmat, EMS, etc.) is discussed. Three real-world events are presented as driving use-cases, illustrating the use of data during an event through a structured approach that fuses (1) what information is needed, (2) for whom, (3) where and how this information is obtained from, and (4) how and when it is presented to the end user.

Keywords

situational awareness
sensors
geographic information systems (GIS)
data-driven approaches
dashboard
visualization

10.1 Introduction/Motivation

The key goal of creating a Smart Fire Fighting environment is to develop the means to deliver accurate, near real-time data (i.e., intelligence) to first responders in a manner that is easily understood, consistent across jurisdictions, and takes into consideration the significance of task and/or data saturation of the user. For example, incident commanders (ICs) handling a structural fire require timely and accurate awareness of the evolving state of the structure, its surrounding environment, and people involved (victims and responders) on which to base actions, plans, and interventions to enable effective operations to save/protect individuals and contain the event.

Delivery of the data during an event is of utmost importance because it is where the "rubber meets the road." Without an appropriate means of delivering data to the responder in a useful manner, the collection of data pre-event becomes less relevant to overcome the obstacles faced during incidents.

In today's environment, the problem is addressed in a variety of methods and complexity. From the simplest means of collecting data on paper and retrieving that data manually during an incident, to highly complex systems integrated together to provide a common operating picture, jurisdictions across the country have developed their own individual systems for transferring pre-event data to incident responders. There are too many varieties of systems to describe for the purposes of this document. It is important to identify that the scope of the issue today begins at pencil and paper systems.

There are several factors which affect the ability of individual jurisdictions to address the delivery of actionable data to first responders during an event. These factors include, but are not limited to, the resources available to each jurisdiction and the functional capability of those resources. For example, a jurisdiction with no IT infrastructure is very resource limited in delivering accurate, near-real-time information to first responders. Another limitation is the relative importance of such information to each jurisdiction. If we assume that each jurisdiction places importance on personnel safety, there is adequate motivation to achieve the necessary results. It is important to recognize however, that each jurisdiction may prioritize this information in different ways. A jurisdiction, who views personnel safety as the physical barrier of protection, may prioritize data lower than personal protective equipment or response apparatus. Other jurisdictions, with enhanced access to resources or funding, may find that data is a high priority because they have already addressed protective clothing and apparatus. In essence, the diversity of the fire service today creates a variety of starting points to begin addressing this issue.

10.2 Literature Review and Summary of Current State of the Art

Much of the industry-related periodicals and research have been highly focused on solving very specific problems. To address a more diverse industry, it is important to review the variety of publications that address technological topics related to incident response.

There are a variety of national standards and codes that have begun to address the issue of data collection and exchange within the fire service. These documents are creating the standards by which information will be collected and exchanged. They have not begun to focus on the means in which data and information is, or will be, utilized by the responder and the ways in which it will be relevant.

The availability of literature for event response is significantly limited. Much of the available material is specific to individual technologies (i.e. radios, mobile data computers, Geographic Information Systems) but do not address the responder specifically. As we have seen in 2013/2014, research efforts that have been happening for years are beginning to see more widespread adoption within the industry. Efforts to publish research, manufacturer technical reports and end-user usability reports should see an uptick as the industry sees value in this method.

10.3 Where Is the Starting Line?

Today's environment within the fire service is an example of extremes. In many of the affluent communities within the United States fire fighting technology is at its most cutting edge. With businesses and residents holding a high technology acumen, these agencies have both the financial resources and the community expectation to use technology to its fullest. Meanwhile, at the other end of the spectrum are economically depressed communities with only the resources to maintain staffing and equipment at its most basic level. In between is a range of communities with various levels of technology adoption. The most basic considerations include the following:

- Fire fighter safety (protective clothing and SCBA)
- Fire staff effectiveness (CAFS, lighter protective materials, basic **sensors**)
- Fire department efficiency (low cost technology, less capability, less interoperability)

Only a small proportion of the fire service in the U.S. has the ability to perform research and development on new technologies as they develop. Staff time for R&D competes against the constraints of adequate staffing on the fireground. It is not uncommon to see training divisions take on the bulk of equipment testing and development. These are commonly the only opportunity manufacturers have to gain valuable feedback from pseudo-operational staff.

Another common method for development is to spend a tremendous amount of time researching, developing and testing a product and only then being able to put the technology into the hands of operational fire fighters. Much of this is due to liability concerns to take untested and marginal equipment into hazardous environments with a chance of failure during a live event. It is common to hear chiefs refer to being on the "bleeding edge" of technology as a place they prefer not to put their department. Chiefs today would much rather see a tested and proven product they can purchase, leaving manufacturers struggling to seek out departments with unique circumstances where they can test their products.

This disparity in technology and testing within departments can be a significant barrier to the effective use of technology. In many cases, this disparity is not across state lines, but as close as the nearest neighboring department. As shown in examples in this chapter, departments, which share borders, can find themselves working together with radically different technologies. This provides another challenge in the development of technology on the incident scene as systems that do not encompass all fire fighters on the fireground are seen as lacking and cause command level distractions that can put safety at risk.

There is a significant need for centers of innovation directly related to the development of fire fighter technology that can establish base standards from which all departments can benefit. These centers can provide not only development assistance but also testing for standards approval. This innovation model is being used effectively in many other industries and can be adapted for the fire service with the right leadership.

10.3.1 Making Strides

In recent years, the fire service has seen significant strides by manufacturers and suppliers to improve the technological capabilities of the responder. There is a range of applicable products emerging in the market, including sensors, materials, tools, and software techniques that aim to create and maintain a real-time information flow to onsite responders.

Functional tools and gadgets such as the thermal imager have drastically improved the capabilities of fire service personnel to overcome obstacles common during events. More recently, geographic information systems vendors, such as ESRI, have led the industry in delivering pre-event information to event responders. Much of this research and development has occurred in cooperation with individual jurisdictions with an emphasis on creating a marketable product. The fire service, as a whole, has only seen marginal advances influencing manufacturers and suppliers to develop industry-wide advances in technology. Early adopters of the thermal imaging devices were able to do so through grants or significant jurisdiction resources. It was through these early adopters that manufacturers were able to reduce the costs associated with development and bring down the initial costs to make the products available to many more jurisdictions. Through time and further technological advancements in manufacturing, the industry has seen significant market penetration of thermal imagers and today it is common for many jurisdictions to see at least one or more thermal imagers in use.

Much of the practice today uses the raw information from gadgets to guide further actions. However, more sophisticated **situational awareness** (SA) tools and technologies that can translate the raw data to actionable information are required.

10.3.2 A Crossroads — Which Way Forward?

Without any alteration of fire service involvement, marketing and sales projections will continue to drive technology advancements. As a result of NIST and other Smart Fire Fighting efforts, it is anticipated that fire industry involvement will become more influential in the research and development of technologies that make sense.

Geographic information systems (GIS) are an example of a use of technology that has become a standard across the industry. While there are prominent vendors in the space, the time and affordability has shown that persistence of a good idea pays off. GIS is not specific to the fire industry. Within public agencies alone, the use of the technology has been shown to be invaluable to the planner, administrator, engineer, communicator, and the first responder. A prominent system in today's workplace, GIS did not become what it is today overnight.

It is important as we discuss areas that need specific consideration, to look at an overall model that encourages adoption of new technologies and the means to bring them to market.

10.3.3 Situational Awareness for the Fire Service

The quality and timeliness of situational awareness (SA) greatly impacts the effectiveness and safety of fire fighting, thus the safety of individual fire fighters. In a 2008 report of a study of factors that contribute to fire fighter injuries in the U.S., situational awareness problems contributed to 37.3 percent of the injuries [1]. SA requires acquiring knowledge of past events, understanding of present circumstances in context, and anticipating future events. It also requires a high degree of communication and coordination up and down the chain of command, as well as between peers, be they individual fire fighters, company officers, the incident commander (IC) and assistants, or dispatchers providing additional resources. Endsley's seminal work [2] defines SA as three increasing levels of understanding of a situation as follows:

1. Perception, where elements of the current situation are observed
2. Comprehension, where information obtained through observation is combined and interpreted
3. Projection, where sufficient information and understanding exists to make predictions about impending events and the effects of possible actions

First responders are well aware of the importance of actionable SA. Extensive efforts are made to ensure that decision makers (e.g., ICs) receive timely access to accurate and reliable information about the incident, the state of the infrastructure, and of available resources. However, a number of factors [3, 4] work against maintaining SA in the context of fire response, including incomplete, inaccurate, or uncertain information, absence of information prioritization, incomplete information sharing, difficulty using the radio with breathing apparatus, many fire fighters using the radio channel simultaneously, and cultural factors.

Determining the right path forward for data use on an incident scene is directly related to those who are actively engaged in making the incident safer and making fire fighters more effective and efficient. As generations of fire fighters emerge with a vested interest in planning, preparing, maintaining, and using data for incident response, the path forward will become clear.

10.4 Technology Gaps, Outputs, and Outcomes in Support of Research

10.4.1 Research Challenges

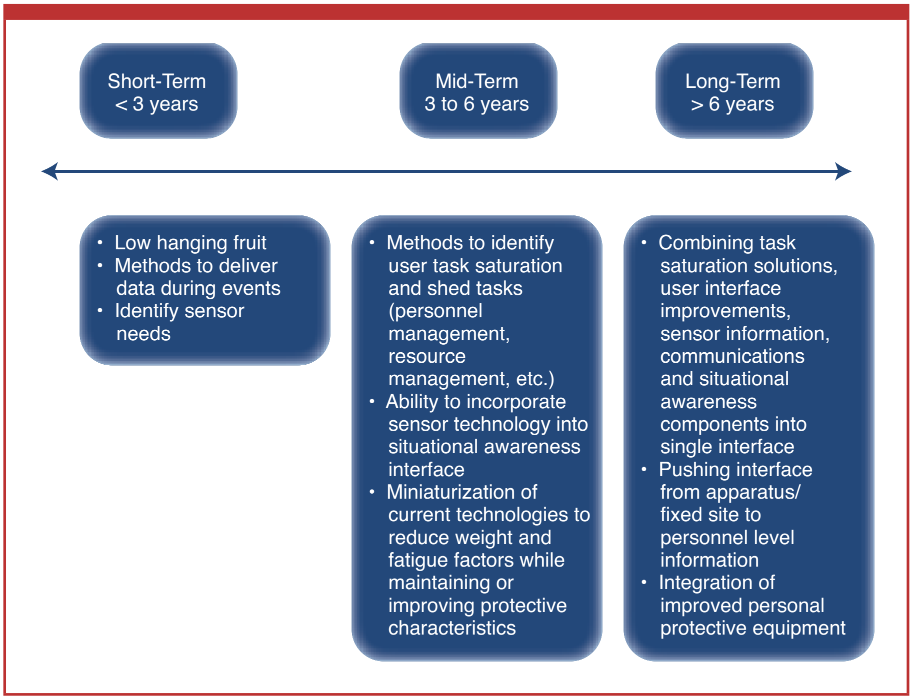
Today's research appears to be supplier driven, until recently when various non-profit or government organizations have taken up the task of focusing on technology research. Individual jurisdictions, many of which are sub-state level governmental agencies, do not have the financial or workforce resources to research and/or develop new technologies. Research dollars have only recently begun to move at the national level to look at national challenges. Again, the diversity of individual jurisdictions creates a needs gap that national solutions will be either too general or too specific to meet cost-benefit analysis metrics. Because the fire service in the United States is a sub-state level responsibility (not to exclude federal and state fire agencies, but only to show such large agencies are only a small overall percentage of the industry), adoption of technology is much the same as the consumer market with the same interests and trends that many consumer technology companies strive to meet.

In addition, the unpredictable nature of events occurring prohibits real-time testing on project timelines. Much like the aviation industry, the fire service must rely on simulation to extract the same level of research parameters necessary for viable results. On larger scale events, such as multi-jurisdiction wildfires or disasters, the testing protocols can quickly conflict with real-world protocols for mitigation. Public expectations to resolve the event will always prioritize well above research opportunities.

Specific research outcomes that can address technology and knowledge gaps would include the following:

- Classification of information needs and recent device usage practices at different levels of the fire practice (to be gained through field studies at a range of locations that capture levels of technology adoption in fire departments around the nation)
- Design of flexible situational awareness platforms for different members of the fire industry
- Design of new data collection platforms and methodologies
- New integrated communication methodologies for reliable and real-time delivery of content gathered at the fire site
- Easy to use interfaces for communication including **dashboards**, speech-based interaction mechanisms, smartphone apps, and so forth
- Research Output — Event Situational Awareness User Interface: realistic simulation of event timelines and variable injects to test the ability of quality data retrieval and understanding — integration of all other management systems to create usable on scene situational awareness (i.e., Personnel Management, Resource Management, pre-event information
- Research Output — Personnel Management: realistic simulation of physical and psychological demands on event response personnel

Figure 10.1 Timeline of research needs for targeted decision making.



- Review of existing and available technology methods versus anticipated new technology/methods
- Timeline of research needs (i.e., short-term, <3 years; mid-term, 3–6 years; long-term, >6 years)
- Timeline of research needs — Targeted Decision Making (see Figure 10.1)
- Magnitude of research needs, with consideration of perceived cost and required resources (e.g., research staff, facilities, materials, etc.)
- Metrics to measure progress and success (e.g., data collection and assessment)
  - Market penetration (percentage of departments utilizing technology nationwide)
  - Capability assessment (performance analysis programs)

10.5 Proposed Approach

We propose a structured approach to the design of new methodologies for the fire service that is able to address needs of personnel/stakeholders under different types of situations. Inherent to the approach is the ability to effectively utilize and merge new cyber-physical system (CPS) technologies as appropriate to improve both automated and human-in-the-loop response to fire events.

1. Determine target scenarios; stakeholders, their goals and needs.
2. For each scenario, construct a table that summarizes needs.

10.5.1 Upcoming and Future Technologies

The key goal is to create a situational awareness platform that can deliver targeted information to the various stakeholders identified earlier. This requires translation of the CPS infrastructure into SA information required for the fire service. To ensure meaningful deployment, the sensor management and interpretation technologies must be designed to easily integrate into existing fire fighter monitoring systems. The ability to take low-level data streams, interpret these streams and extracts

Figure 10.2 Example of incident level awareness tool. (Source: Courtesy SitStat by Psomas.)

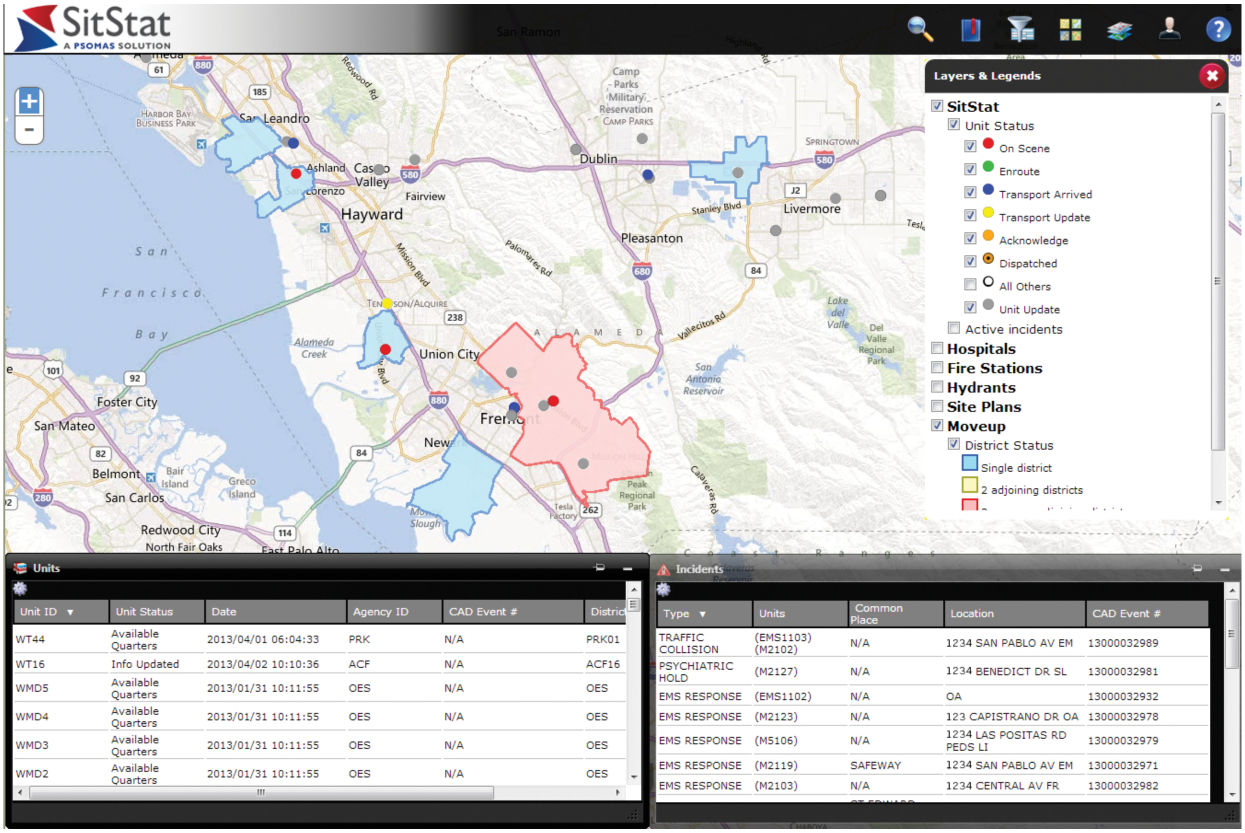
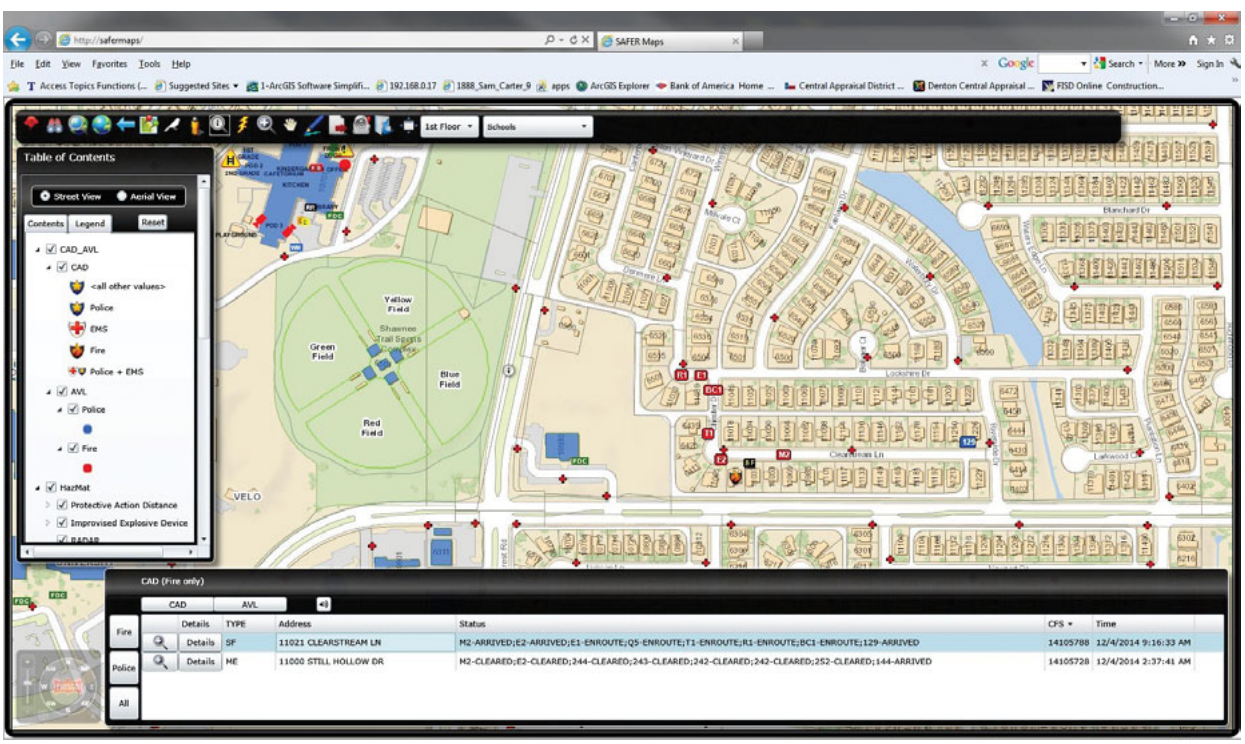


Figure 10.3 Example of incident level awareness tool. (Source: Courtesy of the city of Frisco, TX.)



awareness from the stream, and actuate response processes according to a rules-based schema is critical in realizing this. Technologies to provide individual notifications as well as incident commander notifications in the event of a dangerous condition (e.g., CO exposure levels reach a pre-determined limit) are essential given potentially large volumes of information generated in an autonomous fashion by sensing platforms. Incident level situational awareness tools (SAFIRE, SAFER), which incorporate technologies such as Ebox (a community tool for providing electronically resources such as floor plans, hazmat information to the response personnel) and GIS are integral to creating SA (see Figures 10.2 and 10.3).

10.5.2 Plausible System Architecture for Decision-Making During an Event

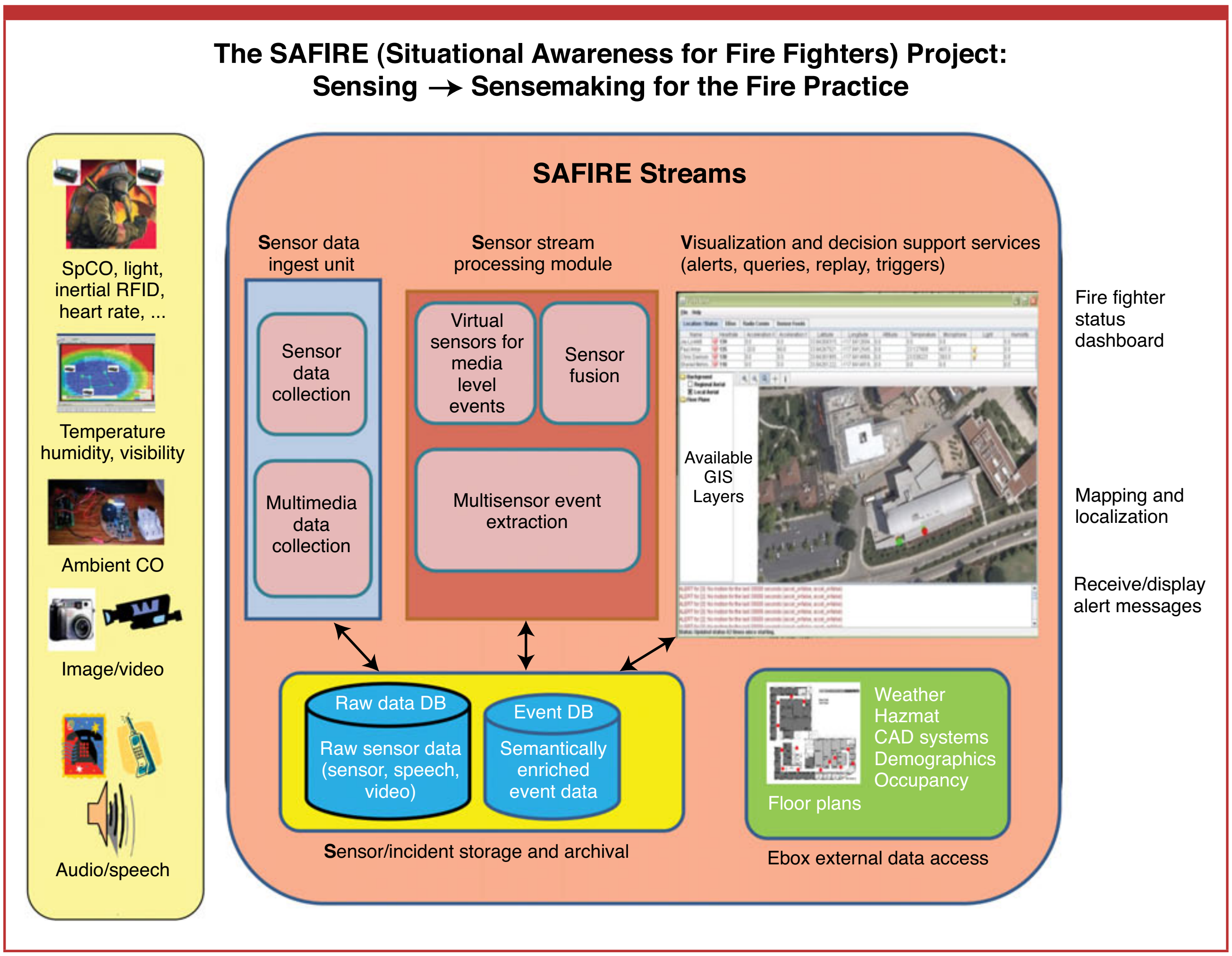
We list and describe four major components of an end-to-end situational awareness system below (see Figure 10.4).

Robust networking and sensing involves the following: (1) improving network signal strength of commercial mesh-router systems through fabrication of an easily deployable omnidirectional high-gain antenna array; (2) developing new wearable carbon monoxide environmental sensor; and (3) designing a store and forward data mule architecture for robust sensing even when networks are intermittent.

10.5.2.1 Data and Metadata Repository

The architecture must include well specified data repository. A simple example is the EBox component of the SAFIRE platform. for providing access to live smart-building data streams such as surveillance cameras and pre-existing data such

Figure 10.4 SAFIRE system architecture.



as floor plans. We note that some of this data is proprietary. To accomplish granting access to private data streams as mentioned above, future research should focus on designing and implementing standardized system components such as those described in [1]. The authors describe the EBox system, which "can be viewed as a software and information analog to the traditional concept of a 'knox-box' — a small safe located outside a building holding its master keys so that responders can quickly obtain and use them in a response situation." This system aims to open sensor streams and internal building data during emergencies for use by first-responders and emergency coordinators, such as 9-1-1 dispatch. Clearly such access should not be granted to just anyone and so a method for authenticating only authorized individuals and establishing audit trails must be established. This may require building chains of trust and identifying proper security policies to enforce them. Such a system would also require standardization efforts for interoperability and presenting a consistent and usable interface to emergency personnel, as explained throughout this section. The repository must incorporate data from the flexible indoor localization using multiple localization technologies and facilitate alert triggering based on information captured from fire fighter radio conversations.

10.5.2.2 Stream and Data Management

The following are elements of stream and data management:

- *A localization framework is an integral part of gathering SA from mobile entities (people and devices).* Initial mechanisms implemented in the SAFIRE Streams middleware and integrated with the fire incident command board user interface indicate the value of this technology. This localization framework provides an interface for a variety of different localization technologies to be merged intelligently to provide incident site location tracking of fire fighters, or of other mobile sensors. The advantages of this approach include improved performance versus single technology localization implementations, and adaptability under varying demands for precision and cost to achieve good location tracking. Several localization technologies were implemented in this framework, including GPS, a WiFi access point fingerprint scheme, Bluetooth beaconing, and speech recognition.
- *A simplified sensor management user interface must be created.* This could be designed as a web-based application that allows deployment of new types of sensors using the SA streams subsystem.

10.5.2.3 Visualization

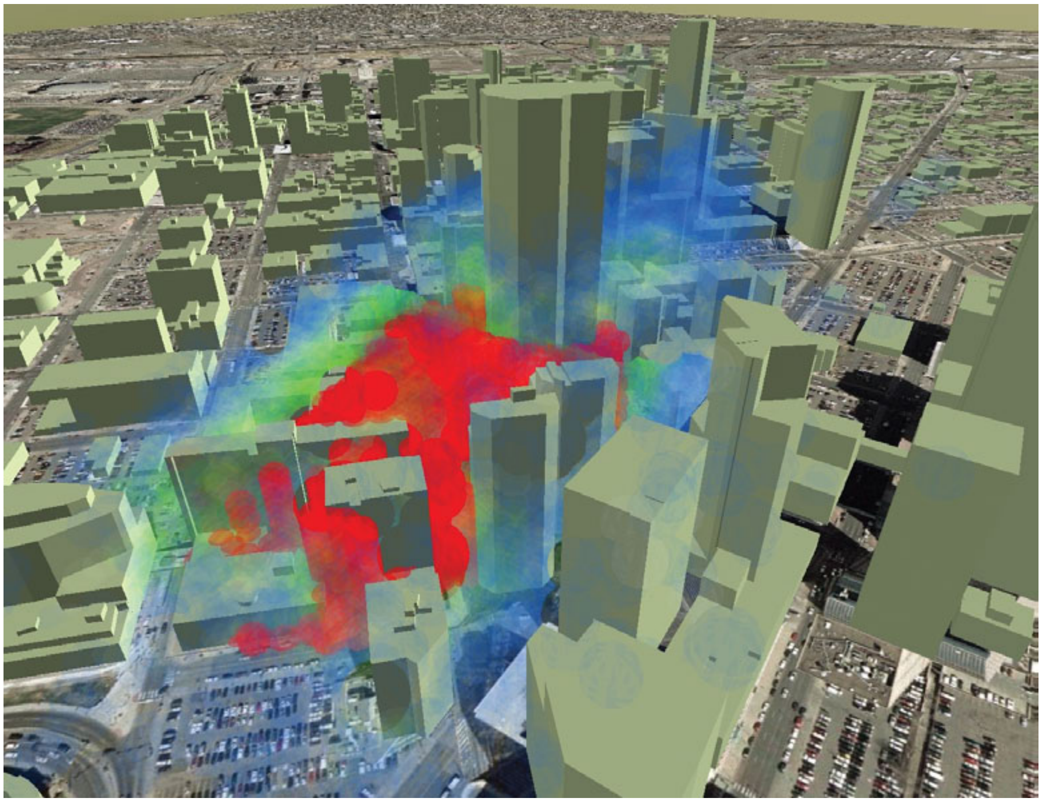
The goal is to have a display that is simple and intuitive enough to give the IC an overview of the fire-fighting operation in a single glance (see Figure 10.5). Displays that are too complicated or have too much information become a distraction from the task of managing the fire response. The viz platform should include items that help in planning or reminding of tasks that are running behind in completion will aid in more effective and safe fire response. This will require the design of novel computer aided dispatch and a sensor inventory systems that represent the state of new information and devices as they become available. Consider, for example, a fire incident command board presented on a portable machine with interfaces for fire site information.

The following address various elements of **visualization**:

- A prototype of query and playback module that can be used to review data collected during an incident after the fact. The prototype synchronizes the playback of multiple different types of data (e.g., video, audio, environmental sensor data) so an incident can be re-experienced.
- Improvements were made to the visualization of fire fighter locations on a map/floorplan in conjunction with the incorporation of the new localization framework. The visualization provides the capability to view the best probabilistic representation of where the fire fighter is located, or a simplified "best-known" position point. Fire fighter physiological and environmental monitoring screens were also improved.
- The IC display is based on the SA server and runs on a regular, providing full access to all the capabilities of this existing SA infrastructure.

In the following three sections, we will illustrate how to use the SA framework described above for three distinct fire scenarios that capture the diverse nature of events that the fire practice must be capable of handling.

Figure 10.5 Example of a plume visual. (Source: Courtesy of the National Center for Atmospheric Research.)



10.5.3 Use of Data During a Structural Fire

To create an understanding of problem, goals, information needs, sources, and criteria during a residential/structure fire, we begin by articulating a residential structural fire scenario. Table 10.1 provides details for a scenario involving a residential structure fire.

On a very warm evening, 9-1-1 dispatchers receive a call from a neighbor reporting smoke coming from the house next door. All units check en route and the first engine (E1) will arrive on scene at 6.5 minutes, 2nd (E2) at 7 minutes and stage at the fire hydrant, 3rd (E3) at 8.5 minutes and report to the scene. The truck (L1) will arrive at 7 minutes and park on the A/B corner with overhead clearance to deploy their ladder. The ALS unit and battalion chief arrive simultaneously at 8 minutes. E1, the first arriving engine, arrives on scene with the following size up:

E1 is on scene with heavy black smoke pushing from the windows and doors, there is a vehicle in the driveway, no one standing outside. E1 will be conducting a walk-around of the structure and deploying an inch and a half to the front door to prepare for entry for search.

E2 arrives at the fire hydrant approximately 250 feet from the B side of the structure and, per standard operating procedure (SOP), lays from the hydrant to E1 automatically.

Ladder 1 (L1) arrives at the same time as E2 and heads directly to the scene. The L1 captain assumes command at the front of the house but offsets his command post to the A/B corner due to the wind blowing smoke into the front yard and street. The L1 captain, now IC, instructs the E2 crew to complete supply to E1 and then report to command.

Table 10.1 Residential structure fire scenario.

Areas of Impact	Scenario Details
Structure	• Single-family home • 4 bedroom, single story attached garage, 2,500 square foot ranch style home • Exterior: 80 percent masonry with composite shingle roof, built after 2005, wood-frame, wood-truss roof system • Interior: typical interior finishes and typical interior furnishings
Environment	• 10 pm local time • 88 degrees • Heat index of 93 degrees • Clear skies • Wind 10 mph from the C side of the structure (blowing into the ICs face)
Fire Conditions	• Kitchen fire • Room and contents fire • Significant smoke penetration throughout the rest of the structure down to 2 feet above floor level, thick black smoke pushing from openings, lighter gray smoke drifting from eaves and roof penetrations
Emergency Response	• 3 engine companies (including 1 mutual aid engine) • 1 truck company (100' aerial ladder) • 1 advanced life support (ALS) ambulance • 1 battalion chief (incident command)

The E1 captain reports from inside the structure she is encountering heavy smoke conditions, but they believe they have located the fire near the kitchen and are attacking the fire. They request assistance searching the home.

The ALS unit arrives and sets up incident safety. The battalion chief arrives and after receiving a transfer brief, assumes command from the L1 captain. He then orders L1 to report to the interior crew, E1, and perform a search of the residence.

A mutual aid engine (MAE1) arrives on scene and reports to command. Command orders MAE1 to set up both the rapid intervention team and establish the positive pressure ventilation fan at the front door.

Command notifies the E1 captain that the PPV fan is at the front door and ready for their request. E1 receives the information and requests the fan be turned in as they are confident they have found the seat of the fire.

The ALS unit, now Incident Safety, reports to Command that they are receiving a personal accountability safety system (PASS) device alarm for E1-4.

Command, per SOP, locks down the radio channel with “Emergency Traffic” and requests a situation report from the E1 captain. MAE1 inches closer to the door with their RIT equipment, preparing to enter the structure to seek out the fire fighter who may be in trouble. The E1 captain reports all members are accounted for and no emergency exists. Command releases the channel again and resumes fire attack operations.

The E1 captain reports the fire is under control and that smoke evacuation needs to begin. MAE1, hearing the report, begins to walk around the structure without orders and knock out all the glass in the windows and open the doors to the home.

L1 completes the search, and is able to retrieve one person from the back bedroom who is suffering from smoke inhalation. L1 turns over the patient to the ALS unit on scene and both members treat the patient. The incident safety position has now been abandoned.

After MAE1 crew's action with the windows and doors, the positive pressure fan is no longer working effectively and the structure is ventilating naturally.

E1's crew completes extinguishment of the fire and begins to overhaul the kitchen. L1 completes a secondary search of the structure and is unable to locate any further victims. MAE1 completes their actions and returns to the A side of the structure and stands by their RIT equipment. The ALS unit has treated and packaged the patient for transportation to the hospital. They check in with command, reporting their destination hospital.

E1's crew doffs their SCBA to complete overhaul. The IC overlooks the ventilation protocol requiring air testing of the structure prior to removing SCBA inside. Fire fighters go to work inside the structure, breathing in the toxins found in the air immediately after a fire, including carbon monoxide.

Command reports the fire is out and begins to put units back to service as salvage and overhaul operations begin to complete. The fire investigator arrives on scene and begins to interview the first arriving engine crew to develop a timeline of the incident.

A reporter has arrived on scene and in between tweets and posts about the fire operations, asks the incident commander for additional information about the patient that was transported and the cause of the fire. Using a camera phone, the reporter takes photos of the fire fighters, sitting in the front yard with their coats and SCBA off, drinking water and talking with the fire investigator. Most of them have beat red faces and can't seem to drink enough water.

An evaluation of the fire and its response process yields interesting insights. In the above scenario, there were differences in ventilation practices between the department and the mutual aid engine company, resulting in ineffective ventilation of the structure post-fire. The ladder company was not assigned their normal assignment of ventilation and this created the above situation. L1 found a patient and brought them outside to the ALS unit on scene, this pushed the ALS crew to patient care and left the incident safety position unstaffed. This domino effect put the responsibility of fire fighter safety in the hands of the IC, who was busy running the incident. As a result, the IC overlooked the ventilation protocol and potentially put fire fighters working inside at risk to inhalation dangers. The fire investigator arrived on scene and began to develop their understanding of the fire from the first arriving units and interviews with the home owners. Arson is considered a very difficult property crime to solve, so a tremendous amount of effort must go into developing a timeline of the fire both pre- and post-9-1-1 call.

In today's environment of instant information, it is not uncommon for the story of the fire to be out in the public well before an incident commander has time to prepare a statement or assign a public information officer. Reporters and citizens can post photos and make statements about the fire without much input from incident command, or any agency representative.

Lastly, the condition of the fire fighters is concerning because of their red faces and only stripping off coats and SCBA. The physiological condition of each fire fighter can be different and so their ability to recover in these conditions will also vary. It is important that command have an understanding of their recovery before sending them back into the structure, or releasing them to respond to other emergencies.

When this scenario is compared to the actions of fire fighters 30, 20, or even 10 years ago, it can stand out as a very different response to a single-family suburban home fire. Technology in materials, tools, equipment, and other areas has altered the methodologies of the fire service. By establishing a roadmap, we can make similar leaps of technology in a year or even months, which will provide for a safer, more effective, and more efficient fire service of the future.

10.6 Fire Service Information Needs

In the residential fire scenario, very little was discussed regarding the needs of information at that type of fire. If we look at more complex incidents encountered by first responders, we can see the variables encountered as incidents change. These are just examples, and it is important to understand that while we are demonstrating the variation between incident types, these variables can also change between departments, as was discussed in the early part of this chapter.

Table 10.2 shows a matrix of a common fire incident found across the country. The goals of each first responder, who maintains individual and core responsibilities based on their assignment, are identified. An analysis of the types of information needed by each responder helps to understand the complexity of finding, analyzing, formatting, and finally producing the information to the various first responder types in any one solution to provide SA to all.

Table 10.2 Information use in high rise and residential structure fire.

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Goals	Rescue Contain Extinguish	Minimal involvement on typical scene – scene safety	Same as fire fighter, EMS, and hazmat plus – Scene safety, resource management, decision-making process	Same as fire fighter, EMS, and hazmat plus – Scene safety, resource management, decision-making process	Same as IC but at higher resolution for specific division/group	Jurisdiction management while event occurs Support of event through resources
Information Needs	Victims Exposures Size-up of conditions	Air monitoring of combustible materials	Fire fighter wellness/ status information Command information – NIMS, accountability, safety Resource tracking, assignment (command board) Conditions – progression of the fire	Fire fighter wellness/ status information Command information/ NIMS, accountability, safety Resource tracking, assignment (command board) Conditions – progression of the fire	Same as IC but at higher resolution	Situational awareness of jurisdiction resources/ events Support – informational, situational, real-time monitoring of event Real-time communication of needs from IC Information and resource delivery to the event IC
Information Sources	Caller/scene indicators/ active distress call Maps/visual size-up	Sensors on scene, sensors carried by fire fighters	Sensors on fire fighters Situational awareness information – situation, resources, safety systems (PASS – SCBA) Building information – pre-event and real-time info (elevators, smoke evac, suppression system)	Sensors on fire fighters Situational awareness information and real-time info (elevators, smoke evac, suppression) Building information – pre-event and real-time info (elevators, smoke evac, suppression system)	Same as IC but at higher resolution	Jurisdiction – GPS/AVL, personnel/ resource status/info Events occurring Event support – On scene sensors, status info from resources and IC, networked situational awareness

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Interoperability	Notification-critical	Medium	Long term – industry is looking for high levels of interop Short term, high	Long term – industry is looking for high levels of interop Short term, high	Same as IC	Same as reliability – high rise facility would likely require mutual aid resources increased demand for interop
Reliability	Caller/ notification – critical Maps for exposure – low/mid priority Maps for event location – critical	Medium	Basic info – critical Safety info – critical Advanced situational awareness – medium	Basic info – critical Safety info – critical Advanced situational awareness – medium	Same as IC	Reliability needs are based on level of support Minimal support needed, less crucial High level of support (high rise) more crucial
Security	Low – minimal priority	Potential – low, if trade secret information - high	Same as EMS, hazmat	Same as EMS, hazmat	Same as IC	Same as EMS, hazmat
Human Interaction Constraints	Labor intensive position, difficult to manipulate tech or data services Dexterity is extremely limited FF is "encased" in protective system for protection, must look at astronauts, deep divers, and others who operate inside environmental protection systems to find dexterity solutions Physical Stress, mental stress	Same as fire fighter, encapsulated person, decon from chemicals, radiation, biological, explosive materials Intrinsically safe?	Outside environment (worst case), loud scene sounds, bright daylight, dark night, weather, flashing strobes, intense scene lights, mobile requirement (vehicle and/ or person mounted)	Outside environment (worst case), loud scene sounds, bright daylight, dark night, weather, flashing strobes, intense scene lights, mobile requirement (vehicle and/ or person mounted)	Same as IC but even more likely to be exposed to elements, remote from vehicle, located in higher levels of building, within building (shields radio transmissions for voice/data)	Task Saturation, task management, mental stress

10.7 Use of Data During a Wildland Fire

In this section, we articulate the goals and needs for creating situational awareness for use by various participants in the wildland fire service. Wildland fire fighting is an extremely scalable type of incident in which the smallest may only require one or two units to control up to hundreds and even thousands of units, the biggest of which can last weeks or months. Table 10.3 helps describe the information needs, sources and factors that influence the use of information. These information needs are obtained and extracted from a variety of stationary, in-situ, and mobile information sources with varying degrees of information quality and reliability. A key point to note is the degree of data interoperability and device compatibility is a critical missing piece that merits further research.

Table 10.3 Information use in wildland scenario.

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Goals	Rescue Contain Extinguish	Rescue Evaluation Transport	Minimal involvement on typical scene – scene safety	Same as fire fighter, EMS, and hazmat plus – Scene safety, resource management, decision-making process Large organizational structure requires more information from remote sources to maintain SA	Same as IC but at higher resolution for specific division/ group	Jurisdiction management while event occurs Support of event through resources
Information Needs	Victims Exposures – structures, natural fuels, natural fuel breaks Size-up of conditions Situational awareness of conditions as they change Resource management at large scale	Victims Triage assessment Resource management Receiving facility status	Air monitoring of combustible materials	Fire fighter wellness/ status information Command information – NIMS, accountability, safety Resource tracking, assignment (command board) Conditions – progression of the fire	Same as IC but at higher resolution	Situational awareness of jurisdiction resources/ events Support – informational, situational, real-time monitoring of event Real-time communication of needs from IC Information and resource delivery to the event IC

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Information Sources	Caller – scene indicators – active distress call Maps – visual size-up Weather stations – aerial assets/ sensors	Size-up/fire fighters – triage officers – patient chief complaints Medic/ ambulance – receiving facility – communications (dispatch)	Sensors on scene, sensors carried by fire fighters	Sensors on fire fighters Situational awareness information – situation, resources, safety systems (PASS – SCBA) Building information – pre-event and real-time info (elevators, smoke evac, suppression system)	Same as IC but at higher resolution	Jurisdiction – GPS/AVL, personnel/ resource status/info Events occurring Event support – on scene sensors, status info from resources and IC, networked situational awareness
Interoperability	Notification-critical Multi-agency response - high	Interop between triage and transport critical – interop between agencies – high Interop with facilities - high	Medium	Long term – industry is looking for high levels of interop Short term, high	Same as IC	Same as reliability – larger wildland events would likely require mutual aid resources increased demand for interop
Reliability	Caller/ notification – critical Maps for exposure – low/mid priority Maps for event location – critical	Mid-range priority	Medium	Basic info – critical Safety info – critical Advanced situational awareness – medium	Same as IC	Reliability needs are based on level of support Minimal support needed, less crucial High level of support (large or long term fire) more crucial
Security	Low – minimal priority	Information security – high-critical due to HIPAA	Potential – low, if trade secret information – high	Same as EMS, hazmat	Same as IC	Same as EMS, hazmat

(*continues*)

Table 10.3 (*Continued*)

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Human Interaction Constraints	Labor-intensive position, difficult to manipulate tech or data services Dexterity is extremely limited FF is remote, in wilderness or areas without technical infrastructure Physical stress, mental stress	Labor intensive, universal precaution (gloves, eye pro, splash pro, etc.) Decon of bodily fluids necessary	Same as fire fighter, encapsulated person, decon from chemicals, radiation, biological, explosive materials Intrinsically safe?	Outside environment (worst case), loud scene sounds, bright daylight, dark night, weather, flashing strobes, intense scene lights, mobile requirement (vehicle and/ or person mounted) Larger incidents may have established fixed IC post, more infrastructure available, less visibility on event	Same as IC but even more likely to be exposed to elements, remote from vehicle, located in higher levels of building, within building (shields radio transmissions for voice/ data)	Task saturation, task management, mental stress

10.8 Use of Data During a Special Event (e.g., Hazmat, EMS, Tech Rescue)

The nature of these types of incidents provides a high degree of variability in overall incident information collection, processing, and production. Hazardous materials incidents can be at a fixed location, from a transport vehicle such as truck, train, or plane; or in a residential garage. The availability of information and the critical clues it can provide to reach a successful outcome can be as important as how that information reaches the hazmat technician. Emergency medical services (EMS) incidents can be similar in complexity. One advantage in today's healthcare system is the common adoption of technology resources by everyone in the industry. It is not uncommon for the patient to have medical information stored on a phone or other device, a hospital to have historical information on a patient or even the EMS agency to be able to obtain diagnostic tools in the field to provide immediate, life-saving care, all due to technology advances adopted early and often throughout the industry.

Table 10.4 is an effort to capture these complexities and provide them. It does not exclude other sources of information, information needs by responders, or human factors that exist currently.

Table 10.4 Special event — hazmat (information needs and sources).

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Goals	Rescue Contain Extinguish, eliminate hazard, reduce hazard or provide for safe stand-off distance	Rescue Evaluation Transport	Heavy involvement broken into three main categories Research/ command – entry – decon	Same as fire fighter, EMS, and hazmat plus Scene safety, resource management, decision-making process	Same as IC but at higher resolution for specific division/group	Jurisdiction management while event occurs Support of event through resources
Information Needs	Victims Exposures Size-up of conditions Continual monitoring of conditions for SA	Victims Triage assessment Resource Management Receiving facility status	Air monitoring for chemical/ biological/ radiation/ explosives Weather monitoring for wind, temp, humidity (dispersion factors)	Fire fighter wellness/ status information Command information – NIMS, accountability, safety	Same as IC but at higher resolution	Situational awareness of jurisdiction resources/ events Support – informational, situational, real-time monitoring of event Real-time communication of needs from IC Communication with extra-jurisdictional agencies and resources (manufacturer/ private agencies/ government response or support agencies, investigative agencies) Information and resource delivery to the event IC Coordination of evacuee safety, security, and housing Recovery efforts to return event site to pre-event safety and status

(*continues*)

Table 10.4 (*Continued*)

	Fire Fighter	First Responder (Medical)	First Responder (Hazmat)	Incident Commander	Division/ Group Supervisor	Emergency Operations Center
Information Sources	Caller – scene indicators – active distress call Maps – visual size-up – Sensor sources – man-portable, vehicle, or fixed mount Manufacturers, vendors, suppliers, facility operators, NIST, USCG CHRIS Manual, electronic chemical data sets, CHEMTREC Other special ops or hazmat teams	Size-up/fire fighters – triage officers – patient chief complaints Medic/ ambulance – receiving facility – communications (dispatch)	Sensors on scene, sensors carried by fire fighters Man-portable, vehicle, or fixed mount sensors for continuous monitoring of weather and air sampling Resource tracking, assignment (command board) Conditions – progression of the release/ dispersion	Sensors on fire fighters Situational awareness information – situation, resources, safety systems (PASS – SCBA) Building information – pre-event and real-time info (elevators, smoke evac, suppression system)	Same as IC but at higher resolution	Jurisdiction – GPS/AVL, personnel/ resource status/ info Events occurring Event support – On scene sensors, status info from resources and IC, networked situational awareness Coordination of federal/state/ local resources (VTC, phone banks, WebEX, etc.) Dispersion and updating of public information Monitoring of shelter facilities, coordination of transport of victims to shelters Long-term tracking and management of recovery process

10.9 Evaluation, Validation, and Technology Transfer

Evaluation of SA tools for the fire service has to look at the opportunities to effectively test and validate the effectiveness of the tool for the end user. Simulation, as previously discussed, is the safe environment for early stage evaluation. Validation of the tool's effectiveness can be established through both simulation and training. Utilizing fire fighter training scenarios can be an effective and controlled environment for obtaining buy in from the eventual users.

Proper packaging and ruggedization of the designed and developed systems is critical at this point so that they can be tested (in testbed exercises) and deployed for use. For example, a technology assessment at a live burn exercise was held Feb. 23, 2014 with the Anaheim F.D., Orange County Fire Authority, and LA County F.D. The goals of this study included calibration of wearable carbon monoxide sensors, assessment of commercial carboxyhemoglobin sensors in a field setting (e.g., structural fire), and off campus (UC-Irvine) deployment of the SAFIRE FICB and supporting systems. Ample data was obtained for the calibration goal. Fire fighter movement caused some false readings to be made by the commercial carboxyhemoglobin monitors but improved sensor design will likely filter out or eliminate these readings.

A situational awareness assessment using the SAGAT methodology was conducted during an exercise held at UC-Irvine on May 12, 2014. In the simulated hazmat incident, one IC had access to the SAFIRE system while the other relied on more traditional technologies (radio). The results of this experiment are being analyzed for inclusion in an article or technical report. A SAFIRE usability study was conducted at the May 17th SAFIRE fire fighter forum as part of a tabletop exercise, in order to evaluate improvements in decision making due to enhanced situational awareness provided by the SAFIRE system. Results indicate a high degree of both usability as well as decision making impact (by virtue of increased information and enhanced situational awareness) in those respondents with incident command experience. Qualitative feedback was also captured in the study.

The fire service has always relied upon the transfer of technologies from other industries. In the case of the thermal imager, a Department of Defense technology was transferred to the fire service and has changed the methodologies of many departments. Thermal imagers have been credited as the primary tool that has allowed fire fighters to save victims from residential fires. Ruggedized computers, cellular phones, tablets, gloves, and even Velcro have all been technologies that have been adopted by the fire service to improve safety, effectiveness, and efficiency.

One area of note, which has seen some dramatic improvements in situational awareness in the past few years, has been the military aviation industry. Significant advances in SA for pilots have seen some remarkable opportunities for first responders. Heads-up display technology has become more compact than ever before, and has seen improvements that allow for directional influence on the viewed information. Applying these advancements to the fire fighter, provides a platform for SA systems and tools to be delivered to the fire fighter "hands-free."

As discussed previously, first responder agencies in the U.S. do not have the pooled resources to research and develop solutions, so it is critical to use technology transfer opportunities from other larger agencies who have spent the time, effort and resources to obtain advancement.

10.9.1 Perceived Future Trends for Technology Adoption

Technical barriers today include the ability for event data capture and storage, pre-event data display without overwhelming the user, and miniaturization of various technologies in an effort to push the technology to the individual responder without tether to a larger power supply or processing capability.

As we have seen with camera phones, texting, and social media, incident data and images are being captured closer and closer to the actual event. In many cases this data and images are being viewed by the public well before first responders have the opportunity to see them. The future holds solutions to providing this data to first responders in a meaningful way.

As we see more and more sensors, data sources, image capture, and monitoring information being collected, first responders will find themselves "task saturated" by everything being thrown at them. With the first mobile data computers, we saw push back from fire officers who would ignore, or in some cases turn off, the computers and the wealth of information they could provide. The officers would instead rely on older, tried and true methods. Task saturation will likely become a barrier as technology advances and more and more information is pushed to the fire fighter.

Even as fire fighters adapt to the changing technology horizon in the industry today, much of today's adoption rates are related to the diversity of the industry. Resource rich, forward leaning jurisdictions will have the opportunity to act as early adopters, while resource limited, prioritization-focused jurisdictions will be limited as late adopters when funding becomes available and/or other priorities have been satisfied.

One challenge to identifying future trends is the variables that influence mass adoption throughout the industry. Many of these variables are related to economic and workforce resources available to apply to emerging technologies. Another variable is the motivation for adoption of technologies, which dictates a future trend. A jurisdiction that adopts due to an injury or fatality within a jurisdiction is much more likely to maintain that technology. If that injury or fatality is identified widely throughout the industry, the likelihood of industry adoption is much higher. On the other hand, if a jurisdiction adopts a new technology, such as building system notification, the likelihood of a future trend developing may be low as the disparity between jurisdiction's priorities may impact adoption. A city with tremendous growth, has the ability to apply building technology because their facilities are recently constructed or under construction. A city with minimal or even negative growth is less likely to adopt building system technologies because their opportunity to invest in new facilities containing the technology likely does not exist. These challenges also confront the use of data during an incident because the same influences that impact pre-event data collection also impact the resources available to adopt event-driven data and usage.

10.10 Future Research Problems and Priorities

The following is a summary of prioritized outputs and outcomes needed to implement new technologies:

1. Phasing of outputs and outcomes: The ability to generate actionable situational awareness from multiple sources will be greatly simplified if there are common and well established standards of interoperability among data formats and exchange mechanisms. This is especially critical to leverage a **data-driven approach** to creating SA that is quickly becoming state of the art. Forums for the standardization of basic information representations, collection formats, and its utilization during events are essential to widespread usability. Such standardization also applies to standard equipment used in the field by fire personnel; in particular, protective technology standards must include sensory data collection for event use and prioritize what types of sensory data will help in meeting safety standards during actual events.
2. Clarification of key stakeholders and their roles in developing solutions: As highlighted in this chapter, there are multiple stakeholders who require multiple functionalities to create meaningful awareness for rapid decision making during events. We list below future needs to bring Smart Fire Fighting capabilities that will benefit both the individual fire fighter safety and effective overall operations in the fire practice.
   - Protective clothing for the fire fighter and safety apparatus on site: New technologies that create novel possibilities for non-intrusive monitoring of both fire fighter health and environmental factors can be incorporated into protective gear in multiple ways. These include sensory integration into protective clothing and enhanced materials that can together reduce fatigue factors associated with responding to an event. On-site apparatus with improved safety features (e.g., through utilization of in-situ or rapidly deployed sensory capacities) can increase the efficacy (speed and reliability) of data collection at the fire site.
   - Improved communications to fire personnel and on site: Enhanced communications capabilities are required for improving the speed, reliability, and efficacy of rich data transfer enabled by new devices. Future communications will occur over multiple communication channels/networks/technologies and this transfer is often bi-directional (used both for data collection and dissemination). The interoperability of the next-generation communications platforms requires further work.

   To enable widespread use and practice of new technologies listed above, cooperation with standards bodies and enforcement mechanisms to ensure adherence to standards and codes (e.g., those established by NFPA, NIST, OSHA, NIOSH) are critical and require closer interaction between technology providers and standards bodies.
3. Review of technological challenges and other barriers that can impede application: Technology challenges range from extraction of meaningful SA from sensor data collected using data-driven methods, ensuring continuously available and accurate, reliable SA during the event to the more operational aspects of interoperable standards and equipment maintenance. Barriers to adoption may arise due to both economic and infrastructure constraints. The costs of additional technology can/will create barriers to acquiring technology, especially in initial stages while research and development dollars are being recovered. On the infrastructure side, gathering and using dynamic data from the event (crucial to the data-driven approach) implies the availability of necessary technology infrastructure such as wireless coverage, storage capacities, and technical assistance and/or support.
4. Anticipated impact of successfully implemented research: The benefits to the fire practice of an approach that implements data-driven situational awareness are enormous and span *safety, effective utilization* of human and equipment resources, and *efficient response* to large and small events. In particular, it will enable improved safety of personnel and citizens during events, improved effectiveness of personnel/resources during event cycle, and improved efficiency of response assets to mitigate events.
5. Reliable and timely data collection architecture over intermittent networks: Reliable and timely data collection from multiple sources lies at the heart of creating actionable SA and improved decision support. Given the failure-prone nature of the infrastructure during fires and emergency events, data collection must be built over intermittently available networks and resources. Techniques to build seamless connectivity for data collection include mechanism to use any and all available infrastructure and information. One such approach is the exploitation of multiple communication technologies simultaneously for reliable delivery of mission critical information [Zhijing-MINA, Ngoc-SRDS, Manoj-ABC, Bo-INFOCOM]. The ability to translate existing research in this area into

the fire practice requires further research. On the information side, mechanisms for dealing with data error and uncertainty are essential in the fire context with potentially malfunctioning devices and sensors. Techniques such as fusing data from multiple sources and sensors, data cleaning methods, and improved information extraction techniques can aid in creating a more accurate picture of the current environment, fill in missing data gaps, and calibrate the fidelity of received data [Ronen-MMCN, Liyan]. This can help guide and adapt the data collection process based on information need [Han-sensor].

6. Spatial tagging and alerting mechanisms: Sensory data from humans and devices are typically associated with locations. The spatial information is essential for effective response. For example, during an event, fire fighters need information about the health, location, and proximity of the current team and company they are engaged with. Much of this information today occurs through a fire fighter's radio—speech is a heavily used modality in the fire practice today. Tagging fire fighter speech segments with keywords and the associated semantic location information, such as "injured and need help in boiler room," can help the fire personnel help citizens and help rapid intervention teams help fire personnel in need of assistance. Effective dissemination strategies are needed to reach fire personnel during events. For example, when sensors indicate undesirable levels of toxicity in the environment, notification through multiple channels and audiovisual methods will result in better outcomes.
7. Scalable storage, retrieval, and presentation of multimodal streaming data: In the emerging future, both fire sites, citizens, and fire personnel will be sources of streaming multimodal data (sensors, speech, video, images, etc.). Computational resources and storage mechanisms will be required to cope with increasing volumes of information. Information extraction methods from multiple data sources will require significant compute power that may not be available at the crisis site. Further work in supporting scalable infrastructure for emergency response, using for instance, cloud-based technologies that are becoming popular today, are being explored. The key challenge for the fire practice is that much of the existing technologies do not support the real-time nature of fire information needs. Ultimately, the ability to support scalable data collection, storage, processing, and dissemination in real-time over a stressed infrastructure is needed. This is a topic that will engage researchers and practitioners in the years to come.

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CHAPTER 11

Non–Fire Fighter Data User Applications

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Abstract

The potential range of cyber-physical system (CPS) functions in the area of non-fire fighter data user applications is broad. To focus our attention on areas with the most research potential, this chapter includes only what we view as the highest need and most feasible applications. We also clearly define the four user applications we chose and identify one or two high-need applications in each. The four areas are defined as call processing centers and emergency point of contact, emergency medical receivers, the general public and building occupants, and government administration.

After an overview of existing systems in the application area, we discuss the current and future research and development efforts regarding business goals, interoperability, security/reliability/scalability and human interaction.

11.1 Overview

The four application areas and organizational units, outside of fire-fighting personnel, determined to have the highest need and greatest feasible potential for user applications are the following:

- *Call processing centers and emergency point of contact*. This user application most commonly refers to 9-1-1 call centers. We divided this area into two types of applications: those that require manual intervention and those that automatically intervene/alert.
- *Emergency medical receivers*. In this case, the focus is on hospitals and emergency care facilities. The primary user applications for this category are the enhancements that could be made between patients, ambulance crews, and hospital receiving facilities.
- *General public and building occupants*. This area focuses on targeted **alerting** and emergency **notifications** as well as general CPS applications targeted at civilians — in particular smartphone apps.
- *Government administration*. It is possible to make a case that in a significant emergency response event almost all aspects of government have a relevant role. Combine this with the fact that every public sector organization is organized differently, and the need to select specific user applications to focus on is immediately clear. We selected two areas that appear to have the most potential for intelligent CPS applications: transportation systems and **risk-based inspections**.

For each of the above application areas, this chapter first provides an overview of existing systems in the respective domains and then discusses the current and future research and development efforts regarding the following aspects of the relevant technology and science:

- *Business goals*. Headline measures and general goals
- *Interoperability*. Standardization, system interactions, and retrofitting efforts
- *Security*. System resilience to attacks, failures, and harsh conditions (scalability)
- *Human interaction*. Potential user studies, privacy concerns, and targeting of particular groups, especially vulnerable or disadvantaged individuals

11.2 Call Processing Centers and Emergency Point of Contact (9-1-1 Centers)

This section focuses only on data or applications that are used by the call center for the purpose of their function in first response. It does not include data or applications used by first responders being fed by call centers. For example, a CPS that alerts a call center to an emergency is within the scope of this section. A CPS that a call center uses to transmit information that first responders need to perform their function is not.

11.2.1 Manual Intervention

Traditional call centers handle only those telephone calls initiated by humans. This section discusses augmenting such centers to support media other than telephone calls and the possible CPS applications that such enhancements enable.

11.2.1.1 Existing Systems

Existing call centers almost exclusively handle voice calls, and few call centers are connected with other centers. The Next-Generation 9-1-1 (**NG9-1-1**) initiative, identified by the National Emergency Number Association (NENA) in 2000, seeks to change that deficiency by updating the emergency call processing centers in the United States and Canada to incorporate newer technologies. NG9-1-1 will allow people to send short message service (SMS) messages (i.e., text messages), pictures, and videos in addition to voice calls. It also aims to network the call centers in such a way that emergency contacts can be more easily and quickly transferred between regions. Currently, many dispatchers must manually look up the number for a call center in another region. This network also improves load balancing and failover of call centers during outages and large-scale emergencies.

Currently, home alarm systems are monitored by the vendors, and emergencies are reported to 9-1-1 dispatch by alarm company representatives. Advanced crash notification systems (ACNS) follow an identical model. Clearly, there exists an opportunity for these systems to provide a common interface to advanced 9-1-1 dispatch centers, as described below.

With the increasing pervasiveness of smartphones in modern society, researchers have begun exploring the potential for "citizen reporting" to transform emergency response. We have seen in recent years that individuals will organize online communities during disasters to exchange information [1]. Section 11.4.1.2 discusses the public-centric aspects of this concept in more detail and provides several examples. Researchers have begun exploring this area, and potential areas for organized efforts to produce more widely accepted and used results. Jaeger et al. [2] make the case for community response grids (CRGs), which are potentially more effective than professional responders alone, allowing residents to help each other when "scarce centralized services are overwhelmed by natural disasters and terror attacks." The authors highlight that communications are too often one way (coordinators to public) and that we must explore methods of enabling the public to communicate with emergency personnel and each other to exchange critical information. For example, one could imagine using data collected from the U.S. Geological Survey's *Did You Feel It?* service to identify potential high-casualty zones as indicated by severe damage reported by civilians [3].

The authors of "SCALE: Safe Community Alert Network (a.k.a. Public Safety for Smart Communities)" propose and describe the SMART-C system, an ongoing effort to extract meaningful information from large streams of unstructured text from social media and sensor data from a multitude of devices. They cover techniques such as natural language processing, scalable database systems, and topic modeling to accomplish this [4]. Sakaki et al. [5] demonstrate such a system by accurately and rapidly identifying earthquakes from tweets immediately following them. Palen et al. [6] provides a comprehensive overview of emergency management via social media, identifying key research topics such as what information the public generates, how people self-organize around that information, assessing the accuracy and trustworthiness of the information, information heterogeneity, information extraction, natural language processing, information diversity, security, privacy, data validity, appropriate aggregation methods, and emerging policy issues.

11.2.1.2 Business Goals

The business goals of implementing NG9-1-1 in call centers would focus on cost minimization and technology scalability. Government agencies are under constant financial pressures, are subject to uneven funding streams, and are chronically understaffed. The ability to scale solutions is key to successful technology advancements. There are currently many commercial data aggregators that could be rapidly modified for public safety. Citizen-initiated data generation and aggregation have already been demonstrated in large disasters, in particular wildland-urban interface (WUI) fires [7]. Commercial web-based technologies could be utilized with sufficient security, privacy, and redundancy protections. Further research would be needed to fully understand technology initiation, governance, and ongoing costs.

11.2.1.3 Interoperability

We envision NG9-1-1 going beyond multimedia feeds and eventually providing a unified interface for data from other sensors, such as smoke, gases, and other events. Such an interface would provide dispatch with a richer view of an emergency, skipping the "middle man" in the case of data coming from an instrumented home or building that currently requires another operator to contact 9-1-1. This would be particularly helpful if the resident or a neighbor contacts **emergency dispatch** directly and thus the alarm system operator would not even be involved. It also enables applications such as streaming medical data from smartphones in the field, particularly if the user is incapacitated and unable to read the data to the operator manually.

Technology is currently being developed in Santa Clara County to directly connect computer-aided dispatch (CAD) systems in different public safety answering points (PSAPs) with each other. The project CAD-to-CAD is designed to allow incompatible software systems to automatically share information between systems and PSAPs through secure fiber and microwave lines. Several different CAD software programs are available to public safety agencies, but these platforms currently do not have the ability to directly and automatically communicate with each other. Human intervention by way of a dispatcher is necessary to complete communications between PSAPs as well as private central alarm monitoring stations. CAD-to-CAD is designed to allow rapid sharing of data between PSAPs, creating efficiencies since data do not need to be re-entered by a dispatcher into each system. CAD-to-CAD combined with integrated voice and other technology solutions would allow for virtual PSAPs that could back up each other in the event of heavy call volume, internal disruptions (power failure, computer system crashes), or large-scale disasters.

Clearly, enabling such interfaces requires a standardization effort from organizations like NENA and compliance by device manufacturers and software programmers. We believe that this could build on existing efforts, such as the Common Alerting Protocol (CAP), which supports sending alert-related data from sensors. Furthermore, algorithms for properly interpreting the data in a unified manner across various devices must be developed. Therefore, we recommend that future research in this area focus on providing common abstractions for cross-device compatibility of emergency-related sensor readings and methods for transferring the data to other locations, such as ambulances en route to the scene, to further enhance situational awareness. In particular, algorithms that handle medical data or streams from social media sites may prove beneficial.

11.2.1.4 Security

Due to their potential to cause confusion, panic, or dangerous situations if activated improperly, these systems are particularly susceptible to cyber attacks, failures, or misconfigurations. This becomes particularly important for critical CPS such as the smart energy grid. Novel methods for formally verifying correctness and resilience to failures of or attacks on systems will be crucial in enabling wider deployments and rapid adoption.

Networking and interface standardization of dispatch centers also open numerous possible CPS applications. In particular, load balancing and failover of systems under duress or even during normal operation can improve the reliability and resilience of an emergency dispatch network. However, sharing information and migrating calls between centers introduce possible security and privacy vulnerabilities and so must be approached with care. While many of these issues can be addressed with traditional cyber-security mechanisms, future research to address when and how these transfers should take place is necessary to prepare for the most adverse conditions.

A new use case — made possible with NG9-1-1 and IPAWS-OPEN, an interoperability and alert aggregation platform developed by FEMA (see Section 11.4.1) standardization efforts — is gathering further information from cell phones and building infrastructure. When a call is made to 9-1-1 on a modern cell phone sold in the United States, GPS tracking is forcibly activated. Additional sensors, such as cameras and heart rate monitors, could be activated to send richer information as well. Because this capability would introduce serious privacy and security concerns, a trust model would have to be established whereby such information would be available only when manually initiated by an authorized individual (a 9-1-1 dispatcher who logs the activation for later audit) or when an emergency is automatically detected and confirmed (e.g., an activated pacemaker sends a secure signal).

To accomplish granting access to private data streams, future research should focus on designing and implementing standardized system components such as those described in Section 10.4.2.1.

11.2.1.5 Human Interaction

Because a person usually physically communicates an emergency with dispatch operators, human interaction is paramount in future advances. Research should focus on not just how to present information clearly to dispatchers and allow them to manipulate those views to gain important information but also how persons in distress interact with dispatch. For example, hard-of-hearing individuals must be able to access alternatives to phone calls for reporting emergencies. Integrating SMS, picture, video, and sensor data streams are one step toward these goals by providing alternative methods of conveying information to dispatch.

Beyond integration of new communications media, we predict a broader use of citizen reporting, particularly in larger disasters, where responders' resources are stretched thin and the public can contribute meaningfully to situational awareness. Because citizens have already begun organizing online communities during disasters, the research in this domain should focus on giving them the tools to organize effectively. Citizens' actions should assist emergency responders, not interfere with their efforts. Citizens should provide accurate information and take appropriate actions in response to information from other citizens. Future research should focus on creating user interfaces that allow easy and intuitive interactions for individuals to report meaningful information and make use of that information.

In addition to — and sometimes at odds with — usable interfaces, research must also enable systems to parse information and add it to geographic information system (GIS) databases for use in emergency operations. Starbird and Stamberger [8] suggest that emergency management organizations "train" citizens to craft tweets and other social media messages in a specific machine-readable format by first broadcasting the format via social media. Shultz et al. [9] discuss a mobile application, Incident Reporter, used by professionals and civilians to report emergency events. The authors define a set of incidents and an associated semantic graph, encoded using the Resource Description Framework (RDF), that gives the pertinent information to include in reports and how to determine when multiple reports refer to the same event. They also define a "common sense vocabulary for citizen users" to report incidents along with rules to match incident labels with domains (fire, police, civilian, etc.). Further research of this type, especially rigorous user studies to identify concise interfaces and intelligible vocabularies accessible to wide audiences, will clearly aid in transforming citizen reports into meaningful situational awareness for emergency responders and coordinators.

11.2.2 Automatic Intervention

Due to inaccurate devices and algorithms, few systems will automatically contact emergency call centers to report events. Many call centers have policies against such systems for exactly that reason. This section explores the few existing systems that do automatically contact 9-1-1, prototype systems that may do so in the future, and our vision for future applications enabled by potential hardware and algorithmic advances.

11.2.2.1 Existing Systems

Home security systems and Automatic Crash Notification Systems (ACNS) require human operators to actually contact 9-1-1 in an emergency. In California, the City of Palo Alto PSAP emergency 9-1-1 center directly monitors over 500 fire and hazardous materials alarm systems at Stanford University. This is an unusual arrangement — most commercial alarm systems are monitored by third-party companies that then retransmit alarm information to PSAPs. This innovative arrangement creates time efficiencies because the alarm is transmitted straight to the fire, rescue, and emergency medical services (EMS) dispatcher. This direct PSAP transmission, which eliminates the third-party, saves one to three minutes, a crucial amount of time in an emergency.

11.2.2.2 Business Goals

The primary business goal would be to minimize or eliminate human data entry between the alarm system and PSAPs. With sufficient quality control and governance, automatic intervention has the opportunity to significantly reduce costs of alarm monitoring and retransmission from a central station to the PSAP.

Advanced technology solutions could be established to monitor multiple data streams, alarm information, security cameras in the immediate area of the alarm activation, and CPS technicians to rapidly determine with a high degree of confidence the presence of legitimate alarms. Further, policies could be developed in PSAPs that require contact with CPS technicians, facility staff, or other technology or human observers on site prior to fire, rescue, or EMS resources being deployed. Such quality control systems would serve to minimize false alarms.

Automatic systems could also be capable of monitoring social media in the immediate area to leverage on-site public individuals' acknowledgement of a problem or an emergency. Citizen-initiated data generation and aggregation have been demonstrated in large disasters, in particular wildland-urban interface (WUI) fires [7].

11.2.2.3 Interoperability

To accelerate adoption and deployment of such intelligent systems for improving situational awareness, we recommend researching various techniques and patterns to allow retrofitting of existing infrastructure with the intelligence necessary for CPS applications. For example, existing guardrails could be inexpensively upgraded with simple crash detection sensors that broadcast signals to authorities when a vehicle strikes them. In recent years, new products like SplitSecnd and Automatic have been released that plug into any existing car and upgrade it with advanced automatic crash notification capabilities through the use of a smartphone and standard communications technologies [10, 11]. Investigating further areas where advanced technologies can be integrated with existing ones will help identify common patterns for building such systems and aid in standardization efforts to support many instantiations.

11.2.2.4 Security

Cyber-security and reliability of automatic notification systems are even more critical than their human-initiated counterparts because less human interaction means that flaws are even less likely to be discovered. The research questions described in Section 11.2.1.4 apply here as well, although any reliance on human decision-making does not.

11.2.2.5 Human Interaction

Although this section focuses on automatically alerting authorities to possible emergencies, some systems fall under a hybrid category in which the alert is initiated automatically but requires human confirmation to avoid unnecessary waste of emergency resources. This may be as simple as responding to a text message or a phone call initiated by a smart smoke detector connected with an alerting cloud service, as demonstrated by the Safe Community Alerting Network (SCALE) team during the 2014 SmartAmerica Challenge [4]. Or, it may be as complex as opening access to various sensors in a smart space for emergency dispatch to determine if a real emergency exists. Determining what degree of intrusiveness should be allowed in such circumstances and identifying reasonable policies to address situations when humans are not available to further investigate events are necessary to make these technologies feasible. A 30-second countdown while trying to reach a person before escalating an alert is reasonable in some circumstances, whereas immediately notifying authorities in other situations is necessary.

11.3 Emergency Medical Receivers (Hospitals)

11.3.1 Transporter (Ambulance) and Receiver (Hospital) Enhancements

This section describes the CPS opportunities to enhance the health of the population, improve the patient's experience and outcomes, and reduce healthcare costs. These three opportunities, also known as the Triple Aim under the Affordable Care Act (ACA), are the foundation of the fundamental redesign of the United States' health care system.

A continuum of minimally invasive patient monitoring and transmission in out-of-hospital settings combined with preventative support and early intervention seeks to minimize the adverse effects of chronic and acute medical diseases. When describing patient monitoring, a human being is the "physical" of the CPS designation versus a fixed structure.

11.3.1.1 Existing Systems

The National Emergency Medical Services Information System (NEMSIS) is a national effort to standardize patient data collected by EMS providers. NEMSIS follows the National Fire Incident Reporting System (NFIRS) data collection model. Established in 1973, NFIRS has standardized the collection and reporting of fire incident data.

Existing pre-hospital emergency medical receivers consist of voice and data transmission between emergency medical technicians (EMTs) and paramedics outside the hospital and an emergency department nurse or doctor. The transfer of information is limited to voice and patient monitoring information, typically electrocardiogram (EKG) monitoring to diagnose heart attacks.

Computer-generated and handwritten reports are currently the accepted means of data transmission although Federal rules under ACA-mandated electronic recordkeeping. As of January 1, 2014, all public and private healthcare providers shall have adopted and demonstrated “meaningful use” of electronic recordkeeping in order to receive Medicaid and Medicare reimbursement. Data is often lost when handwritten or verbal transfer of patient information takes place between EMS crews and hospital emergency department staff. It is important to note that the ACA did not fund this electronic recordkeeping mandate, and many public and private emergency medical agencies have yet to fulfill the requirement.

11.3.1.2 Business Goals

Two significant business goals are contemplated. First is the reduction in errors and omissions in data transfer between out-of-hospital healthcare providers and those within the hospital. The second business goal would be to create time-saving efficiencies through the elimination in redundant data entry.

Data generated by the patient’s self-monitoring systems could be automatically transmitted to mobile record management systems (RMS) of out-of-hospital providers, including nurses, paramedics, and EMTs. On-scene assessments and treatments by healthcare providers could be automatically transmitted to medical receiving facilities in advance of arrival. Accurate records would support effective documentation and reduce risk of medical errors.

The elimination of redundant data entry would create cost savings for medical facilities. Currently it takes medical facility staff 10 to 15 minutes to register patients in emergency and urgent care facilities using handwritten documents or creating a second medical record. High-volume medical facilities that register thousands of patients annually could leverage this technology to create significant cost savings.

11.3.1.3 Interoperability

NEMSIS, the national effort to standardize patient data collected by EMS providers, follows the NFIRS data collection model. The NEMSIS project was developed to help states collect standardized elements and to support a national EMS database. To be NEMSIS compliant, software vendors and developers must demonstrate interoperability.

11.3.1.4 Security

Patient privacy mandated under the Federal Health Insurance Portability and Privacy Act (HIPPA, 1996) is the paramount security concern. The Office for Civil Rights enforces the HIPAA Privacy Rule, which protects the privacy of individually identifiable health information and sets national standards for the security of electronic protected health information. The confidentiality provisions of the Patient Safety Rule protect identifiable information used to analyze patient safety events and improve patient safety [12].

It is contemplated that multiple digital platforms would transfer medical records from medical databases to emergency dispatch and then to field units. Field units would input current data as part of their patient care record and then transfer updated information to medical databases and hospitals.

11.3.1.5 Human Interaction

Human interaction in this CPS use is primarily focused on medical record reliability and the connectivity to support the automatic transfer of medical records during emergencies. Emergency medical dispatch (EMD) is a systematic program of handling medical calls. Trained dispatchers quickly determine the nature and priority of the call, dispatch the appropriate response, and then give the caller instructions to help treat the patient until the responding EMS unit arrives [13].

The majority of medical emergency response is five minutes or less, so the time for dispatchers to process, validate, and route the data to users is limited, and EMD would be an additional step that the dispatcher would need to take.

Field users typically would have time to validate and update the medical record as mandated under local emergency medical guidelines to produce a patient care record for every patient contact. The data would then be automatically transferred to the medical facility and the local governmental agencies that provide oversight and medical direction to field personnel. If the CPS system is unavailable, field staff would utilize handwritten patient care records or complete data entry that would be updated and transferred once the CPS was operational.

These CPS systems could also include hospital bed availability, emergency room capacity, supply chain usage, monitoring and ordering of replacement supplies, equipment, and personnel. An integrated CPS system could create follow-up schedules and appointments as well as create an individualized medication database and reconciliation to reduce negative drug interactions and overmedication. The state of California recently completed a study that defined the implementation steps agencies would take to achieve full CPS data transfer [14].

11.4 General Public and Building Occupants

With continuous advances in capabilities and pervasiveness of technology in our society comes the potential to provide more and better information and tools to the general public. Because they are not assumed to possess significant expertise in the area of emergency response, the tailoring of alerts, instructions, and tools to individual needs requires extensive research to enable a society truly prepared to navigate emergencies with smart technology.

11.4.1 Mass and Targeted Notification

When emergencies occur, someone (or something) must notify possibly affected individuals as quickly and accurately as possible with information about the event and recommended actions to protect their personal safety without interfering with responders' efforts. We classify notifications into two categories: mass notifications, which require human intervention due to their broad scope, and local notifications, which allow automatic initiation due to the large number of locales.

During significant widespread emergencies, responsible administrations must notify a broad portion of the public. Due to the number of affected individuals and the potential for greater damage caused by false alarms, notifications must be vetted for accuracy. The complexity of such a scenario may require different recommended actions tailored to specific populations or based on other information contributed by various domain experts. Notification systems are evolving to become more advanced, and the potential exists for creating CPS that provides more intelligent recommendations to key decision makers who then decide how to act based on richer information. That would free up human resources for more complex and pertinent tasks or augment those resources by identifying situations and particular propositions that otherwise might go unnoticed.

Within a local area, individuals may be temporarily subjected to emergency conditions that require alerting a specific group, so mass notification would not be appropriate. Beyond the existence of the emergency, notification might include even more personalized information such as individual evacuation routes or identification of the emergency (e.g., a picture of an active shooter or a staircase on fire that should be avoided). This section also covers automatically generated alerts originating from intelligent CPS infrastructure (e.g., smart buildings).

11.4.1.1 Existing Systems

In June 2006, President George W. Bush signed an executive order to modernize the existing mass notification systems in the United States. In response, the Federal Emergency Management Agency (FEMA) designed a networked system called the Integrated Public Alert and Warning System (IPAWS) that would connect existing and future systems, including the following:

- Emergency Alert System (EAS)
- National Warning System (NAWAS)
- Commercial Mobile Alert System (CMAS)
- National Oceanic and Atmospheric Administration (NOAA) All-Hazards Weather Radio

The IPAWS Open Platform for Emergency Networks (IPAWS-OPEN) aggregates alerts from those multiple sources and distributes them to relevant participants in the IPAWS network. By aggregating alerts from various authorities, IPAWS can rebroadcast them to affected individuals through all the different integrated channels, including the EAS, and via Wireless Emergency Alerts (WEA), which are delivered through cell phones.

On a smaller scale, numerous commercial solutions exist to notify large populations within a local government (city, county, state, etc.) or campus (large corporation, university, etc.). Systems such as Cooper, Everbridge, and Guardly provide the capability to notify registered individuals by phone call, SMS, email, and even computer screen pop-ups about events. Some systems, such as Everbridge, even provide limited capabilities for the public to respond with on-scene details.

11.4.1.2 Business Goals

Timely wireless emergency alerts would support early warning and the ability to take action to preserve life and minimize property damage. Current technology allows for targeted and relevant notification. The primary business goal would be to life safety, property preservation, and environmental protection.

The use of this CPS supports preparation, response, and recovery and ensures continuity of operations for affected businesses and communities. Business continuity is the ability of an organization to provide service and support for its customers and to maintain its sustainability following a catastrophic event.

It is important to limit false notifications and not overload citizens with irrelevant nonemergency alerts. Also, the purpose of the notification must be made clear (i.e., community information versus emergency alert).

11.4.1.3 Interoperability

IPAWS is specifically designed with interoperability in mind so as to connect multiple independent systems that may be from different vendors or administered by different organizations. It is still a work in progress, so we expect to see many new adapters arise as it matures. The majority of the integration efforts have focused on melding different alerting systems, and little research has explored the potential for specific non-alerting systems to integrate with IPAWS. For example, the U.S. Geological Survey currently sends earthquake alerts through IPAWS. Industrial facilities, such as petroleum refineries or large factories, could integrate with local alerting systems through IPAWS-OPEN to alert nearby residents to accidents or potential hazards. CPS-centric integration with various utilities, such as electric, water, and telecommunications, also provides the possibility for this infrastructure to adapt to impending emergencies. Research here should focus on what external information would be useful to the IPAWS network and how external systems can reliably automatically react to such notifications to improve public safety.

IPAWS utilizes CAP to encode alert messages and relevant information. Adopting this standard, which was developed by FEMA and the Organization of the Advancement of Structured Information Standards (OASIS), enables additional systems to more easily integrate with IPAWS, particularly user-facing applications that determine which information to display and how to present it. CAP's alert templates, based on best practices and academic research, can include rich content dissemination by referencing external sources and can target specific geographical regions. Sensor devices can also report events, which can then be aggregated in a centralized location or cloud service, which when combined with other alerts "facilitates the detection of emerging patterns in local warnings of various kinds, such as might indicate an undetected hazard or hostile act" [15]. Future research should focus on integrating a multitude of sensor data with the IPAWS systems using CAP and how the data can be analyzed in a scalable manner to detect further events and possibly issue further alerts automatically or with minimal human intervention.

Many commercial alerting systems have begun integration with IPAWS, although further work is needed to determine how best to make all these systems interact. For example, alerts issued by a local authority could be broadcast through a campus alerting system, but determining how IPAWS should handle alerts coming from a campus system (should nearby residents be notified?) must be addressed as well.

11.4.1.4 Security

To address cyber-security, IPAWS uses well-established mechanisms of authenticating different systems and signing messages to ensure that the contents have not been modified. As sensor devices are integrated into this system, mechanisms for establishing trust without overloading human operators and for detecting physical compromise of the devices are necessary.

Another area of research in need of exploration is how to make use of private data from individuals. For example, when alerts target regions, they are not delivered to recipients until they actually enter the geographic area. If the system could anticipate a user's intent to travel into or through that area (e.g., based on current location and known destination), the user could be notified that it is unsafe to do so and should either shelter in place or route around the region. This requires a mechanism for securely collecting enough data to make such a determination while still maintaining the individual's privacy.

Testing the systems and their interoperations is also necessary. Many authorities are "reluctant to use IPAWS because procedures for them to test all IPAWS components do not exist" [15]. Having such a large-scale distributed system in which some components could fail or become compromised during an emergency introduces a further need for this testing. Especially as more systems are integrated at the lowest levels and the IPAWS-OPEN server is distributed across a cloud network (for scalability and reliability), the interactions between systems will become more complicated, increasing the failure and attack spaces possible. Research addressing how to formally design, test, verify, and audit large-scale CPS will prove critical in the coming years for emergency response and all CPS in general.

11.4.1.5 Human Interaction

Because alerting systems are intended primarily for human recipients, they must be designed with human interaction as a primary requirement. In particular, the systems should be easy to use during high-stress situations and clearly communicate important information to affected individuals without including too much information or sending information to unaffected individuals. A responsible individual must issue the alerts, so streamlining the process of doing so will allow that person to focus more on addressing the emergency in question. Intelligence to pre-populate forms used to create alerts based on information gathered from sensors and analytics would help accomplish this and also mitigate mistakes that might be made by a human making a quick decision during a rapidly evolving emergency. Such intelligence could include accurately identifying the geographic scope of an event with high precision and perhaps generating secondary alerts to individuals outside the affected area who might be traveling or who require slightly different instructions on how to react.

The information contained in alerts must clearly explain actions the public should take in terms that laypersons will understand. Furthermore, they should be accessible to everyone, including disabled individuals such as blind or deaf persons. Research to solve these issues may not all be CPS-centric, but one could envision CPS applications on user devices such as tailoring alert methods to the environment a person is currently in (e.g., visual flashing messages when surrounded by loud noises).

For notifications to fulfill their purpose, recipients not only must be able to understand them but must also trust them as well. If someone receives frequent notifications that either do not pertain to them or are incorrect, the individual might opt out of future warnings. Some systems are opt-in and so must ease these concerns as well for people to sign up in the first place. A University of Maryland study [16] on its campus alerting system identified *perceived usefulness* and *perceived ease of use* as important factors in human-facing alerting systems. They found that students were confused by multiple alerting systems and so recommended that each system's purpose be clearly identified and more visible to students. They also found that students wanted a more customizable system, such as more control over which exact alerts they would receive. For example, clearly distinguishing frequent severe weather alerts from rare events such as active shooters or bomb threats reduces the risk of individuals opting out of all alerts just to ignore a particular group.

11.4.2 Personal Emergency Assistance

Beyond the alerting and emergency call/data receiving loop, a host of applications, usually targeted toward smartphone platforms, to assist the public during emergencies has surfaced in recent years. These applications tend to focus on connecting friends and family, providing information and guidance to help victims, and enhancing mobile device technology to provide various emergency services and tools.

11.4.2.1 Existing Systems

Effective and reliable communications, for both responders and civilians, are one of the most crucial aspects of disaster response. Applications such as FireChat, built on the OpenGarden platform, and Serval allow the creation of ad hoc networks for connecting individuals with smartphones and other WiFi-enabled devices without the need for dedicated and powered infrastructure (see Section 4.3.7.3 for more details). They provide mechanisms for individuals to chat with each other and download/upload resources from/to web services if some node in the mesh has Internet connectivity. We see this technology as enabling various rich CPS applications during disasters, although much research is required in better managing devices and services during severe emergencies in addition to developing the applications themselves. For example, augmenting existing web-based services such as Google's person finder, which helps family and friends location each other after separation, to work within an ad hoc network introduces various network, device, and data management challenges [17].

The Red Cross has created a suite of applications aimed at providing tips for addressing particular natural disasters and providing tools and information for civilians. They include an "I'm Safe" feature that, at the touch of a button, notifies a person's emergency contacts that he or she is okay after an event. The Red Cross Volunteer App helps identify volunteers to assist with disaster response, using push notifications to make requests and allowing users to earn badges, which can be shared via social media, for accepting jobs and completing training, quizzes, and so forth. There exists a clear potential for a CPS application by better identifying who is ideal for a job in some area based on proximity, current health, training, and certifications. An application with a similar concept, called PulsePoint, helps locate nearby individuals who are CPR-certified as well as nearby defibrillators [18]. Beyond recruiting volunteers and more effectively coordinating their efforts, such applications could augment sharing of emergency resources (food, water, clothing, etc.) among civilians as well. This site proposes a match-making application to link victims with resources to those in need, creating a market for exchanging such goods [19]. Beyond this bartering model, we envision a system for posting available resources, making requests, and efficiently coordinating disbursement by volunteers and emergency responders, taking into account urgency of needs, accessibility of locations, fuel consumed to transport goods, and availability of resources. Such a system could be expanded to include locating emergency services, such as emergency rooms, to augment existing and upcoming systems that simply provide information such as emergency department wait times and locations.

FEMA has created a mobile application that, like the Red Cross apps, provides various safety tips for individuals. In addition, it features a disaster reporting feature designed for individuals to participate in citizen reporting (see Section 11.2.1.5) with a process for professionals to approve reports. The FEMA app, as well as others such as the District of Columbia Homeland Security and Emergency Management Agency (DC HSEMA) app, provides a list of open shelters, which we see as having the potential for an advanced CPS that automatically coordinates where individuals should seek shelter and/or evacuate to. For example, victims with certain medical conditions should be routed to shelters equipped to handle them, disabled or unhealthy individuals should be sent to closer shelters when appropriate, and healthy individuals should be sent to shelters farther away in order to more evenly distribute shelter load. This also provides an opportunity for more intelligent and personalized evacuation routes. Currently, coordination of evacuations addresses large groups of individuals, usually demarcated by geographic location. Only through intelligent CPS that exploit current personal status, as captured by sensors and augmented with direct user input, as well as social network relationships can we truly achieve such personalized plans, which may include such metrics as familiarity of routes or location of friends and family members along the way.

11.4.2.2 Business Goals

The business goals for approaches involving personal emergency assistance include the desire of the general population to empower civilians to act in a manner that allows them to take self-preservation steps for their own life and property (e.g., evacuation routes, first aid). This is expanded beyond the individual to include multiple notification systems that connect with family members, company-wide notification, and other personal assets that are deemed high priority. The intent is to connect as many people as possible with timely information to help navigate emergency situations better. This is similar to various mass notification protocols, and also includes collecting data to quantify applications' usefulness. An example is the ability to alert trained medical personal in the vicinity of an individual experiencing a sudden emergency medical condition [20].

11.4.2.3 Interoperability

Standardizing methods for applications and devices to share information during emergency scenarios is crucial for enabling developers to create rich, intelligent, and functional applications. For example, ad hoc communication between devices, especially across platforms, is vital for building large ad hoc networks; otherwise, it would be constrained to devices of the same type (e.g., all iPhones). Furthermore, sharing data between apps (like building floor plans with Google Maps) lets people make use of applications with which they are familiar and have already downloaded rather than forcing them into using a particular one. It also encourages ecosystems of sharing data openly rather than issues of vendor lock-in, which can stifle adoption of services that may provide invaluable benefit.

11.4.2.4 Security

In addition to the previously mentioned security and privacy concerns, the predominant use of smartphones during an emergency involves additional concerns and tradeoffs. In particular, people relying on their smartphones for navigating disaster scenarios necessitates improving their energy efficiency, especially when a charging infrastructure is unavailable. The Smartphone Disaster Mode team demonstrated such an attempt at the 2014 SmartAmerica Challenge Expo [11]. They identified and implemented several tweaks in the Android operating system, such as altering the display color palette. Identifying such techniques is the first step in this process and must be followed by implementation and rigorous testing and optimization. Additionally, because these modifications frequently happen at the operating system level, it requires working closely with system implementers (e.g., Google) to ensure integration and adoption.

Aside from low-level optimizations, use of standard offline web technologies can further improve energy and network efficiency by allowing users to cache larger web app resources in advance or download them only once during emergencies. It has the further benefit of improving resilience to network failures and allowing users to easily access applications without an involved installation processes. Ad hoc networked phones could even be configured to act as web servers for less proactive users to download emergency preparedness applications from more active users who have set up advanced applications on their devices. This could improve availability of the apps during adverse network conditions as well as alleviate some concerns of early adoption. However, because security and authenticity issues will be introduced, identifying proper techniques for correctly signing and verifying such web artifacts will require careful design and novel research.

The Smartphone Disaster Mode team also explored the possibility of learning people's movement abilities, familiar areas, and social contacts for personalized evacuation planning, as discussed in Section 11.4.2.1. Other similar possibilities include knowledge of individuals' medications and health conditions for more effective disbursement of critical resources and routing of refugees. Applications like these introduce severe privacy concerns, so research should focus on enabling those capabilities while preventing false or malicious information from entering the system. Work on verifiable trust networks, possibly based on known social contacts, may help this effort along.

Ad hoc networking introduces a special case of security and energy efficiency. Even more than with traditional infrastructure-based approaches, it requires a careful balancing act of usefulness and security versus energy efficiency. Encryption may provide security and privacy for users, but it comes at the cost of higher overheads and greater energy consumption. Similarly, faster and more reliable communications can be accomplished with techniques such as flooding, but they decrease the efficiency and increase power consumption in the network. Identifying novel techniques to address these challenges, particularly in the context of smartphones and human users, will prove an area ripe for research in the coming years.

11.4.2.5 Human Interaction

In addition to the human interaction considerations from Section 11.4.1.5, a critical area to address in providing CPS for the public is that of incentivizing participation and adoption of these technologies. In addition to the public's perception of possible privacy invasions that may be introduced, perceived usefulness must be addressed. Just advertising applications' features may not be enough, so gamifying them may help increase pre-emergency downloads as well as overall usage. For example, users earning badges in apps like Red Cross can train and educate individuals in addition to providing vital statistics about general preparedness and identifying ideal volunteer candidates. Encouraging pre-emergency download and use also helps users familiarize themselves with the applications, encourages plans to use them, and gets people sharing resources and talking about emergency preparedness in general.

Increasing the pervasiveness of these technologies alone is not enough, however. User research must also address training and encouraging users to utilize these resources properly. For example, ad hoc networking applications must keep individuals from flooding the network with large volumes of noncritical traffic. Identifying the difference between calls for help and leisurely uploading photos to social media sites is difficult, if not impossible, without human intervention. Therefore, education and direct feedback about precious limited bandwidth and how to properly use it may be the only option for enabling such useful systems.

11.5 Governmental Administration

11.5.1 Transportation: Routing and Signage

11.5.1.1 Existing Systems

Although this guide focuses on Smart Fire Fighting, from a non-fire data government administration perspective, you cannot have Smart Fire Fighting without a smart transportation system to move people and apparatus to where they are needed. Even a cursory exploration of various smart transportation systems will result in numerous technologies and systems. These systems constitute their own realm of research, and not all are relevant to this text. However, there are some functions of these systems that overlap with the purpose of this guide. Specifically, these are technologies that do the following:

- Improve response times
- Create flexibility in the transportation network
- Provide situational awareness regarding critical infrastructure
- Create intelligence out of raw video and other data

Following are some current examples of systems and research that begin to explore the connection between Smart Fire Fighting and smart transportation.

- The Center for Advanced Transportation Technology Laboratory at the University of Maryland (CATT Lab) has developed a comprehensive set of tools around information visualization, data fusion, and human interface design meant to improve transportation management during emergency incidents. One particular tool in their portfolio is the Regional Integrated Transportation Information System (RITIS), which combines real-time data and situational awareness to respond to events.
- The work of Dr. Yang Cai, a professor at Carnegie Mellon University, who is working with Pennsylvania Department of Transportation camera feeds to develop better incident detection. This type of capability also could be used to determine the status of bridges and roadways following an incident.
- Another Carnegie Mellon University professor, Dr. William F. Eddy, working with data from the local port authority buses has developed a system to make better decisions on bus routes and service time. This type of analysis could be used to develop systems that adapt in emergency situations.
- The University of Michigan Transportation Research Institute has recently completed research on the effectiveness of personal navigation devices that could prove useful when government officials need to deploy emergency guidance to different personal devices.

This list focused on current research activities rather than commercially available technologies. Commercial systems abound, and although their capabilities are impressive, most focus on traffic management with an eye toward the efficient flow of vehicles in a nonemergency setting. Opportunities for research and public sector–academic collaboration abound when one considers the benefits of aggregating data from open networks of cyber-physical systems.

11.5.1.2 Business Goals

New transit systems and the now almost ubiquitous use of GPS in the management of mass transit are opening up many opportunities for enhanced evacuation systems in the event of an emergency. Fire and rescue services play a critical role in both small- and large-scale evacuations. Whether it involves a mass migration of residents from an area that is or will be affected (e.g., biological or chemical attack with a plume) or a smaller-scale movement around an impacted area (e.g., flood or large fire), the government currently lacks an efficient means to reroute current assets and infrastructure. Currently, fire and rescue services primarily use manual methods to route apparatus to incidents. During significant events, situational first responders are tasked with less "value-added" activities such as traffic management as opposed to ensuring the safety and well-being of residents. A traffic and transportation management system that is adaptable and programmable can free first responders from such tasks and improve mobility for safety apparatus during an emergency. Connected transportation systems can also provide situational awareness to first responders regarding the status of critical infrastructure. Finally, given the long-term outlook of driverless or self-driving vehicles, steps should be taken now to understand the effects on first responders.

First responders also benefit from enhanced situational awareness when infrastructure can communicate directly with their dispatch mechanisms. Connected buses, bridges, and other infrastructure needed for the movement or people and equipment should be able to provide their status to dispatch. For example, after an earthquake, systems like Shakecast (developed by the U.S. Geological Survey and other stakeholders) takes the important step of blending ground motion data with the fragility of critical infrastructure to provide decision-making information to government officials on the estimated status of that infrastructure. An additional layer of sensor data could be added to provide the actual status of the infrastructure. This real-time picture of a situation could be ingested into a transportation modeling system to create instant "pop-up" transit systems that make use of passable and safe routes. All these functions, when equipped with digital, connected signage, can ease the burden of government communications during a disaster. Public confusion and panic following a significant event can be greatly diminished with these forms of enhanced communication.

11.5.1.3 Interoperability

The potential for jurisdictional issues to impede regional systems are obvious. For example, in the event of a large-scale wildfire, a mass evacuation system that must move evacuees dozens of miles will be ineffective if the system stops at the nearest border. Impediments like this will not be an issue until these types of systems become more common, but by the time government agencies begin procuring this capability from vendors, it may be too late to create an interoperable, regional network out of a patchwork of proprietary systems. It may be advisable to research open systems and standards that could enhance regional collaboration.

Beyond the interoperability of the systems themselves, the underlying raw data from these transit systems should be openly available. Specifically, the sensor data feeding these systems could be repurposed for a variety of uses.

11.5.1.4 Security

As with any CPS involving critical infrastructure, security is a serious concern. Factor in the desire for an open system that makes data available to any organization that may benefit from access and securing the system becomes more complex. All the security concerns discussed in the preceding sections apply here. In the intelligent, flexible transportation use case, it becomes more important to secure the devices receiving instructions, and the need to secure the sensor data transmission and receiving methods. Research should be directed at how sensors and devices can be secured as the need to make them smaller and lower power becomes more and more important.

11.5.1.5 Human Interaction

Scenarios under which intelligent, flexible transportation systems and signage are utilized all still require a human factor in the event of a widespread incident. In large, complex situations, most policies still require that an appropriate authority (e.g., mayor, county executive, police chief, governor) make a decision. For the foreseeable future, such a policy is necessary due to the current limitations of the technology and the serious implications of such a decision. In these situations, the systems should focus on giving the decision maker as much clarity about the options that the system can enable. In smaller-scale incidents, such as apartment building fires, serious automobile accidents, and industrial accidents, the system could be designed to trigger automated changes in the transportation network to help keep residents from entering the affected area and assist those in the area to escape safely. This could be done without manual intervention provided the systems effectively communicate with the personal navigation devices in the affected area.

11.5.2 Risk-Based Inspections

11.5.2.1 Existing Systems

Another benefit of increased access to data connected to an increased likelihood of a fire incident is the ability to focus resources on preventative measures. These systems attempt to prevent fires by aiming inspections and other mitigating actions toward those buildings most likely to experience a fire. This predictive analytics approach has been pioneered by the New York City Fire Department and is the primary example of an existing system. This system relies on mined data from various city systems to generate predictive models. Developed under Mayor Michael Bloomberg, the system focuses on at-risk buildings in an area where building fires are already in decline. Although an important example of what can be achieved with thoughtful data analytics, this system is not a CPS. Research into a system that generates predictive analytics based on sensor data should not be confused with research into advanced fire detection systems. Systems like this one are meant to detect the presence of smoke or flames and are already being studied by NIST [22].

11.5.2.2 Business Goals

Many jurisdictions are shifting fire inspections from sworn positions to civilian positions as a cost savings measure. Although the ability to reduce costs by reducing the number of overall inspections may sound appealing, inspections are a preventative measure and play an important role in any jurisdiction. In places with fire inspection programs and proper code enforcement activities, fire-related incidents occur at half the rate as those in places that do not have them. With that in mind, a CPS meant to predict which buildings are at greater risk of a fire should not be used to cut inspections but rather focus on them. The same study that found code enforcement and inspections to be effective also found that a large majority of fires (upward of two-thirds) could not have been prevented by the actions of inspectors due to a variety of factors, including fires caused by suspicious origins or arson. The study also determined that inspections would not prevent fires stemming from mechanical failures and maintenance problems. A sensor network built to detect environmental factors that correlate with an increased likelihood of fire would make these types of fires more preventable by arming inspectors with real-time data and analytics. They also present the opportunity of lowering insurance costs for businesses.

11.5.2.3 Interoperability

Simply collecting and analyzing data to conduct risk-based inspections is a big data project, not a CPS. For an inspection system that continuously monitors for increased risk factors, buildings equipped with sensors should be streaming their data to a portal or hub where those factors can be monitored. Obviously this is a very large challenge given the variety of systems on the market and the effort associated with creating a single dashboard or monitoring tool. To meet this challenge, attention and research should focus on standards and incentives that would allow manufacturers and building managers opportunities to create and install systems that comply with the standards. A similar model already exists for drivers who gather data on their driving patterns. These types of methods could be employed by insurance companies and governments by incentivizing property owners who share their data in compliance with a set of open standards.

11.5.2.4 Security

It is unlikely that any data gathered in these situations would give rise to a realistic security concern if breached. It is not anticipated that any of the building data would contain personally identifiable information or HIPPA-protected data. Since these inspections would not be for single-family homes, most of the data gathered would not focus on any specific residence. It is possible that knowledge of a risk factor might result in additional liability for a property owner, but that would not be the concern of any potential research project.

11.5.2.5 Human Interaction

As pointed out in the previous section, it is unlikely that any private data would be collected via a CPS of this nature. The systems would not be used for emergency response or notification but would augment existing active alarm systems. As such, the human factors for these systems would be less critical because a system failure would not result in a dangerous situation. For that reason, research in this specific area is less critical.

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CHAPTER 12

User Interface Delivery Methods

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Abstract

In order for the user interfaces of Smart Fire Fighting technologies to be successful, fire fighters must be able to achieve specified goals simply and with effectiveness, efficiency, and satisfaction in a specified context of use. Research and development of devices must take a whole-system approach rather than a piecemeal one. In doing so, there must be some standardization not only in all components of the device but also in the acquired and dispensed data and information. Fire fighters need data and information that are effective to the task and the context of use. Consider these three contexts, which are relevant at a level of abstraction for all fire departments: office/fire station, responding, and fire fighting. In addition to those contexts, it is important to understand the user (the fire unit) and the distribution of personnel within the unit across the contexts as well as the speed, accuracy, and urgency of the information that needs to be accessed. In the office/fire station, fire personnel are generally together in a group — one might even say tightly coupled. In the responding context, the unit is more distributed, or loosely coupled where timely, accurate information is required, whereas in the context of fire fighting the unit is highly distributed and the need for accurate information to be communicated immediately is critical. There are implications on connectivity and communications not based solely on the context but also on the distribution of the fire unit and the integration of the device to the members of the unit. The context, the task, and the fire personnel must all be considered in the design of effective user interfaces.

Keywords

user interface
delivery methods
decision making
context of use
usability
human centered design
user testing
Integration
interoperability

12.1 Introduction

The benefits of Smart Fire Fighting technologies such as cyber-physical systems (CPS) [1] and big data can be realized only through effective **user interfaces**. To make the right decision, it is critical that fire fighters receive the right information at the right time and delivered in the right way. John Anderson puts it this way: "The way a user interacts with a computer is as important as the computation itself; in other words, the human interface, as it has come to be called, is as fundamental to computing as any processor configuration, operating system, or programming environment." [2] Donald Norman observes: "We are surrounded by large numbers of manufactured items, most intended to make our lives easier and more pleasant. . . . All these wonderful devices are supposed to help us save time and produce faster, superior results. But wait a minute — if these new devices are so wonderful, why do we need special dedicated staff members ("power users" or "key operators") to make them work? Why do we need manuals or special instructions to use [them]? Why do so many features go unused? And why do these devices add to the stresses of life rather than reduce them?" [3]

ISO 9241-11:1998 [4] defines **usability** as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified **context of use**." For the user interfaces of Smart Fire Fighting technologies to be successful, fire fighters must be able to achieve specified goals simply with effectiveness, efficiency, and satisfaction in their specified context of use. Research and development of devices must take a whole-system approach rather than a piecemeal one. In doing so, there must be some standardization not only in all components of the device but also in the data and information that are acquired and dispensed. Fire fighters need data and information that are effective to the task and the context of use. Three contexts are relevant at a level of abstraction for all fire departments:

1. **Office/station.** While there is huge diversity among fire departments, the office/station context is generally characterized as a typical office setting with Internet connectivity, good available communications, and a controlled environment of heating/air conditioning, electricity, lighting, and background noise.
2. **Responding.** In the responding context, the fire personnel are on the move to a location using their apparatus. The environment is characterized by both the equipment and the act of changing locations. The personnel are generally in full personal protective equipment (PPE) [5] less the self-contained breathing apparatus (SCBA) [6] facepiece and in a moving vehicle. This environment is much less controlled than the office setting, meaning that the internet connectivity, the communications, and the electricity are all less reliable. The physical environment is not as controlled with respect to temperature, humidity, and noise. But, more important, there is a potential lack of rich data as well as the means to access and assess the data quickly.
3. **Fire fighting.** The fire-fighting context is characterized by the extreme conditions of high stress, extreme temperature swings, and visually and physically challenging activities with high noise, low tactile sensitivity, and cognitive overload. Add to those conditions the fact that the personnel may be fully clothed or encapsulated. A fully clothed fire fighter at a minimum is usually wearing a PPE [5] ensemble that consists of a coat, pants, boots, helmet, gloves, hood, SCBA [6], flashlight, and portable radio [7] and carrying a bail-out rope system. Frequently, they are dragging a hose or carrying a thermal imager [8], hand tools such as an axe and/or Halligan tool, a 6-foot-long pike pole, and/or a power saw, in addition to other items in their pockets. The total weight can be anywhere from 75 to 100 pounds or more of equipment. Finally, device connectivity and communications frequently are difficult.

In addition to those three contexts, it is important to understand the user (the fire unit) and the distribution of personnel within the unit across the contexts. In the office, the fire personnel are generally together in a group — one might even say tightly coupled. In the responding context, the unit is more distributed, more loosely coupled, whereas in the fire-fighting context the unit is highly distributed. There are implications on connectivity and communications not based on just the context but also by the distribution of the fire unit and the integration of the device to the members of the unit. The context, the task, and the fire personnel must all be considered in the design of effective user interfaces.

12.1.1 Need for Effective User Interfaces

No matter how good the data from Smart Fire Fighting technologies may be with respect to quality, accuracy, and completeness, if the user interface or **delivery method** is not usable or is confusing, the data are inactionable and could cause harm. The Three Mile Island nuclear power plant accident, the most investigated accident in the history of the commercial nuclear industry, is an example of the consequences of a poor user interface. Because the design of the control room did not emphasize the user interface, operators experienced problems locating and accessing the tools and information they needed. The following interface issues were identified [9]:

- System controls were not located near the instruments that displayed the condition of the system. For example, operators could not view the indicator display for the high-pressure system while operating the throttle valve to adjust pressure.
- Some instruments located near one another looked very similar but controlled different functions.
- Some instruments were difficult to read because of glare from poor lighting or obstruction by other controls.
- Throughout the control room, there was no consistent meaning of indicators (such as lights and alarms) or function of instruments (such as levers and knobs) between controls.
- At the time of the accident, operators in the control room heard three alarms and saw more than 1,600 blinking lights.

The operators were overwhelmed with all the incoming data in the stressful environment. The information was not delivered effectively or efficiently for the operators to make the right decision at the right time. Fire fighters also rely on a great deal of incoming information in stressful situations. Consider, for example, a current proposal for the use of smartphones [10] as a universal communication method utilizing the Internet for emergency personnel. While this device may address many emergency personnel's needs and goals and may be appropriate and effective in the context of the office/station, it falls short for fire fighters in the responding and fire fighting contexts. User input, situational testing, and standardization are critical to the success of any device. Current devices are not ruggedized for the extreme conditions in which the device must function, including extreme heat and water. In addition, a user wearing large, heavy gloves must be able to operate the device. A smartphone's buttons are not big enough, are too close together, and are not sensitive enough for use with fire-fighting protective gloves. In addition, the screen is difficult to read through a SCBA [6] facepiece. All-inclusive application-driven testing must be considered if the smartphone, in its current format, were to become the standard for emergency personnel, replacing current radios; otherwise, **interoperability** could be compromised and fire fighters would be isolated from other emergency personnel and at risk for injury.

Currently, the National Fire Protection Association (NFPA) is developing a proposed standard, NFPA 1802, *Standard on Personal Portable (Hand-Held) Two-Way Radio Communications Devices for Use by Emergency Services Personnel in the Hazard Zone* [7], to address some of the shortcomings of smartphones as well as of land mobile radios (LMRs), which also have been identified as potentially inadequate for the ruggedized world of fire fighting. NFPA is responsible for 380 codes and standards designed to minimize the risk and effects of fire by establishing criteria for building, processing, design, service, and installation in the United States, as well as in many other countries. NFPA's more than 200 technical codes and standards–development committees have over 6,000 volunteers who vote on proposals and revisions in a process that is accredited by the American National Standards Institute (ANSI).

Today, NFPA codes and standards attempt to guide the fire service and the use of technology. While NFPA standards are not mandatory unless adopted into law by a jurisdiction, they represent a form of standardization and reliability for the fire service and ultimately are the benchmark to which a fire department is held accountable in the instance of a fire fighter's death or injury. The death of a fire fighter often causes new NFPA product standards to be created or existing standards to be modified due to the identification of weaknesses or deficiencies in the standards.

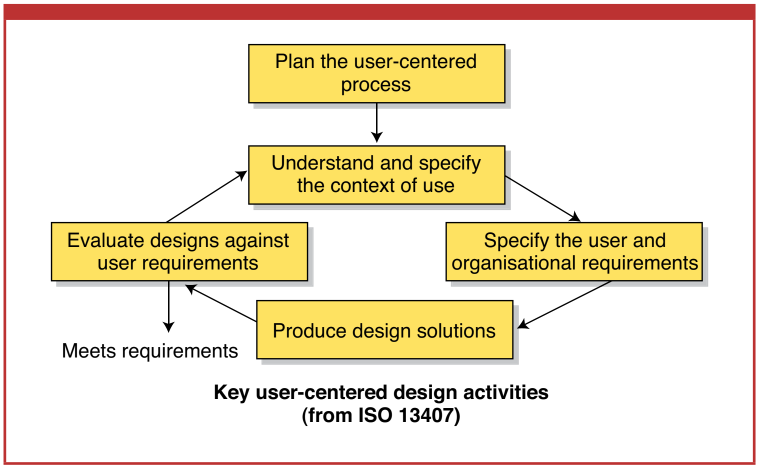
Many new technologies, including means for accountability and physiological monitoring, are emerging today, and attempts are being made to integrate them into the fire service. Unfortunately, little emphasis is placed on the value of the intent and the content of the information that the device will offer to the end user, the user interface, and ultimately the practicality of the device. How much information is too much? What is a practical way to deliver information and have it be relevant? As a rule, fire fighters on the fireground are already overworked due to manpower issues in both paid and volunteer settings and carry extreme amounts of weight.

12.1.2 Current State of Interfaces

Today's interfaces rely heavily on keyboards and touch screens. They are ever decreasing in size (e.g., laptops, tablets, and smartphones) and mobility (e.g., WiFi, GPS). Unfortunately, these interfaces have limitations for fire personnel in the contexts of use described here. Moreover, with the NFPA standards in place, the addition or **integration** of technology must be streamlined, practical, and acceptable to the fire service. Most important is the actual field testing of any new device. Many technologies and interfaces look good on paper, but their actual use versus their intended use frequently exposes deficiencies and oversights in design.

Deficiencies can be addressed by working directly with fire personnel during design and development and by applying **human-centered design** principles and best practices to ensure that new technologies address fire fighters' needs and integrate into the environment. As new user interfaces emerge to facilitate interactions with new computing paradigms such as a CPS [1], the established design principles of the human factors and the usability community will still apply to address the suitability and usability of the interfaces for fire fighters. As devices and interfaces are designed for fire fighters, key design principles must be observed. User-centered design is an approach to the design and development of a system or technology that aims to improve the ability of end users to use the product effectively and efficiently. It seeks to improve the user experience of an entire system from hardware design to software implementation, involving all aspects of a technology. By involving users in the design, development, and evaluation of a system, user-centered design works to create more usable products that meet the needs of the users. Involving users, in turn, reduces the risk that the resulting system will under deliver or fail.

Figure 12.1 User-centered design process.



User-centered design involves ISO 9241-210:2009 [4], an early focus on users, tasks, and environment; the active involvement of users; an appropriate allocation of function between user and system; the incorporation of user-derived feedback into the system design; and iterative design whereby a prototype is designed, tested, and modified.

The user-centered design process, as illustrated in Figure 12.1, includes the following steps:

- Defining the *context* of *use*, including operational environment, user characteristics, tasks, and social environment
- Determining the *user and organizational requirements*, including business requirements, user requirements, and technical requirements
- Developing the *design solution*, including the system design, user interface, and training materials
- Conducting the *evaluation*, including functionality, usability, and conformance testing

Although there is a substantial body of knowledge and research regarding user-centered design and usability principles, much of that information is not yet integrated into the standard design and development processes of today's fire-fighting systems. Fire fighters must be involved from the beginning in defining the requirements, the design solution, and especially the testing of a new or updated technology solution.

12.2 Review of Literature

A literature review was conducted with the assistance of the NIST library services. Databases available through the NIST Research Library were searched to locate journal articles, conference papers, and other documents related to user interfaces and smart technologies for fire fighters. The database Engineering Village was selected for this search because it covers all the major sources of publications in this area of research and includes papers in IEEE Xplore and the SPIE Digital Library, two full-text resources available through the Research Library. Web of Science (scholarly literature) and Nexis (trade literature) were also searched. The search was limited to 2009 through 2014.

The searches identified primarily conference papers and journal articles. Research findings included many papers that discuss Smart Fire Fighting technologies, including wireless sensor networks, smart garments, and fire-fighting robots. Papers described sensors and interfaces for physiological monitoring, situational awareness, location and tracking, communication; sensors in fire fighters' gloves, garments, masks, and helmets; haptic sensors; and sensors for virtual reality. A total of 81 documents were reviewed, including 48 conference papers, 21 journal articles, 10 trade publication articles, a NIST technical report, and a project summary. Conference papers were primarily from various IEEE conference proceedings and journal articles from a variety of journals, including two from IEEE: *Transactions on Antennas* and *Propagation and Sensors*. Only two papers discussed standards and testing of fire-fighting devices.

12.2.1 Summary of Reviewed Literature

Given the rapid development and fluidity of the field, the following summary was confined to the most recent technologies with direct relevance and applicability.

12.2.1.1 Voice/Speech Interfaces

Lovgren, S. 2006. "Silent" speech device may aid divers, firefighters, cell phone users. *National Geographic.* http://news.nationalgeographic.com/news/2006/12/061227-translator.html.

Stein, D., and B. Usabaev. *Automatic Speech Recognition on Firefighter TETRA Broadcast.* http://www.lrec-conf.org/proceedings/lrec2012/pdf/113_Paper.pdf

12.2.1.2 Gesture Interfaces

Acceleglove by AnthroTronix. https://www.youtube.com/watch?v=0i13DGLVZS0

12.2.1.3 Eye Gaze Technology

Anonymous. 2012. EYE-TRACKING: the cool new technology that's changing the world. *The Economist.* http://www.businessinsider.com/eye-tracking-changing-world-2012-12.

Anonymous. 2012. The eyes have it. *The Economist.* http://www.economist.com/news/technology-quarterly/21567195-computer-interfaces-ability-determine-location-persons-gaze.

12.2.1.4 Immersive/Augmented Reality

Augmented Reality Firefighter's SCBA Mask. http://www.youtube.com/watch?v=QBAnr2gQTH0&feature=player_embedded.

Betancur, J. A., Osorio-Gomez, G., Mejia, A., and C. A. Rodriguez. 2014. Smart army helmet: a glance in what soldier helmets can become in the near future by integrating present technologies. S*ensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Security and Homeland Defense.* XIII.

Pei, Q. 2012. Design of the key units fire electronic plans system based on virtual reality technology. *2012 2nd International Conference on Frontiers of Manufacturing Science and Measuring Technology*. 232–235.

Schonauer, C., et al. 2013. 3D building reconstruction and thermal mapping in fire brigade operations. *2013 IEEE Virtual Reality Conference.*

12.2.1.5 Touch and Haptic Interfaces

Carton, A., and L. E. Dunne. 2013. Tactile distance feedback for firefighters: design and preliminary evaluation of a sensory augmentation glove. *Proceedings of the 4th Augmented Human International Conference*. 58–64.

Harris, W. 2014. How haptic technology works. HowStuffWorks.com. http://electronics.howstuffworks.com/everyday-tech/haptic-technology.htm.

Ranasinghe, A., et al. 2013. A two party haptic guidance controller via a hard rein. *2013 26th IEEE/RSJ International Conference on Intelligent Robots and Systems: New Horizon, IROS 2013*. 116–122.

Walters, K., Lee, S., Starner, T., Leibrandt, R., and M. Lawo. 2010. Touchfire: towards a glove-mounted tactile display for rendering temperature readings for firefighters. *2010 International Symposium on Wearable Computers (ISWC)*. 1–4.

12.2.1.6 Wearable Computers, Electronic Textiles and Bio-sensors

Coca, A., Roberge, R. J., Williams, W. J., Landsittel, D. P., Powell, J. B., and A. Palmiero. 2010. Physiological monitoring in firefighter ensembles: wearable plethysmographic sensor vest versus standard equipment. *Journal of Occupational and Environmental Hygiene*. 7: 109–114.

Cooper, D. 2014. Smart shoes vibrate. *Endgadget.* http://www.engadget.com/2014/07/24/vibrating-shoe-navigation/.

Harrington, C., et al. 2013. Self-reporting of firefighter vital signs in emergency situations. *57th Human Factors and Ergonomics Society Annual Meeting.* 1678–1682.

Klann, M. 2008. Tactical navigation support for firefighters: the LifeNet ad-hoc sensor-network and wearable system. *2nd International Workshop on Mobile Information Technology for Emergency Response*. 41–56.

Kumar, P. S., Oh, S., Kwon, H., Rai, P., and V. K. Varadan. 2013. Smart real-time cardiac diagnostic sensor systems for football players and soldiers under intense physical training. *Proceedings of the SPIE.* 8691.

Magenes, G., Curone, D., Caldani, L., and E. L. Secco. 2010. Fire fighters and rescuers monitoring through wearable sensors: the ProeTEX project. *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 3594–3597.

Magenes, G., et al. 2011. Biosensing and environmental sensing for emergency and protection e-Textiles. *33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society.* 8365–8366.

Mrugala, D., et al. 2012. Temperature sensor measurement system for firefighter gloves. *26th European Conference on Solid-State Transducers, Eurosensor 2012*. 611–614.

Rogier, H., et al. 2013. Active textile antennas in professional garments for sensing, localisation and communication. *2013 IEEE European Microwave Conference*. 850–853.

Salej, A., et al. 2011. Application of nickel-titanium alloys (NiTi-NOL) in smart textiles and clothes. *Tekstil*. 60: 123–131.

Salvado, R., et al. 2012. Textile materials for the design of wearable antennas: a survey. *Sensors*. 12: 15841–15857.

Talavera, G., et al. Protecting firefighters with wearable devices. 2012. *6th International Conference on Ubiquitous Computing and Ambient Intelligence*. 470–477.

Where there's smoke, there's a signal. *U.S. Department of Homeland Security.* http://www.dhs.gov/where-there%E2%80%99s-smoke-theres-signal.

12.2.1.7 Vibration Interfaces

Cooper, D. 2014. Smart shoes vibrate. *Endgadget.* http://www.engadget.com/2014/07/24/vibrating-shoe-navigation/.

Lilly, K. 2014. Tactile belts let soldiers feel their way through the field. *Army Times.* http://www.armytimes.com/article/20140629/NEWS04/306290019/Tactile-belts-let-soldiers-feel-their-way-through-field.

Murphy, D. 2013. Tactile helmet uses vibrations to help firefighters 'see' in the dark. *PC Magazine.* http://www.pcmag.com/article2/0,2817,2417265,00.asp.

12.2.1.8 Heads-up Displays

Augmented Reality Firefighter's SCBA Mask. http://www.youtube.com/watch?v=QBAnr2gQTH0&feature=player_embedded.

Betancur, J. A., Osorio-Gomez, G., Mejia, A., and C. A. Rodriguez. 2014. Smart army helmet: A glance in what soldier helmets can become in the near future by integrating present technologies. *Proceedings of SPIE 9074.*

Tarantola, A. 2014. This sci-fi helmet could give firefighters predator thermal vision. *Gizmodo.* http://gizmodo.com/this-sci-fi-helmet-could-give-fire-fighters-predator-th-1563777192.

12.2.1.9 Context Aware and Situational Awareness

Context-aware computing. *Gartner*. http://www.gartner.com/it-glossary/context-aware-computing-2/.

DARPA. From close air support to fire suppression. http://www.darpa.mil/NewsEvents/Releases/2014/06/09.aspx.

Jiang, X., Chen, N. Y., Hong, J. I., Wang, K., Takayama, L., and J. A. Landay. 2004. SIREN: Context aware computing for firefighting. *Research Showcase @ CMU.* http://repository.cmu.edu/hcii/77.

Panangadan, A., et al. 2012. A system to provide real-time collaborative situational awareness by Web enabling a distributed sensor network. *1st ACM SIGSPATIAL Workshop on Sensor Web Enablement*. pp. 24–31.

12.2.1.10 Mobile Devices

Sun, X., et al. A study of fire information detection on PDA device. 2009. *13th International Conference on Human-Computer Interaction*. 105–113.

12.2.2 Applicable Standards and Data Collection Protocols

Several regulatory-based documents are available that relate to the topic of emergency responders and wearable apparatus and communication devices. These documents are generally in the form of consensus-developed model codes and standards and include the following NFPA standards:

NFPA 1801, *Standard on Thermal Imagers for the Fire Service*, which directly addresses thermal imaging cameras used by emergency responders

NFPA 1802, *Standard on Personal Portable (Hand-Held) Two-Way Radio Communications Devices for Use by Emergency Services Personnel in the Hazard Zone*, a proposed standard that directly addresses hand-held two-way radio communications devices used by emergency responders in the hazard zone

NFPA 1982, *Standard on Personal Alert Safety Systems (PASS)*, which directly addresses PASS used by emergency responders

NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting*, which directly addresses personal protective clothing used by emergency responders

NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services*, which directly addresses SCBA and associated electronics used by emergency responders

National Fire Incident Reporting System (NFIRS) is a system established by the National Fire Data Center of the United States Fire Administration (USFA), a division of the Federal Emergency Management Agency. NFIRS is current as of June, 2006, version 5.0, was released in January, 1999.

The following standards apply to human factors and usability definitions in the design process:

ISO 9241-210: 2009 Ergonomics of human system interaction — Part 210: Human-centred design for interactive systems. ISO 9241-210 is a standard developed through the consensus-based process that gives an overview of human-centered design activities and provides requirements and recommendations for human-centered design principles and activities throughout the life cycle of computer-based interactive systems. Intended to be used by those managing design processes, it is concerned with ways in which both hardware and software components of interactive systems can enhance human-system interaction.

ISO/IEC 25062:2006, Software engineering: Software product Quality Requirements and Evaluation (SQuaRE) — Common Industry Format (CIF) for usability test reports. ISO/IEC 25062 is a standard developed through the consensus-based process that provides a standard format for reporting usability test findings. It provides guidance on how to report the results of a usability test but does not indicate how to perform the usability testing.

12.3 Current State of the Art

There is huge diversity among fire departments not just between paid and volunteer but from fire department to fire department. Today's fire fighters face a proliferation of new devices and technologies that attempt to address a perceived need without consideration of the cumulative effects. As a result, fire fighters must overcome the frustration with gear, devices, and technologies and withstand the new additions and the potential consequences. Take, for example, the extreme weight of gear that fire fighters wear and carry in the fire-fighting context. The following sections explore each context of use.

12.3.1 The Office/Station

As a rule, municipalities have their own fire departments, which in turn have their own operating procedures. The fire departments have different capacities and responsibilities, and as a result there may be little standardization in operation and means of gathering or distributing information. Within the municipalities, there may also exist both common and unique fire potential issues that require frequent inspection and pre-planning by the fire department if it is to remain timely and accurate.

Funding in fire departments is frequently lacking; available money is usually lopsided, with the greatest portion allocated to suppression, personnel, and equipment. Far less funding for both time and resources is aimed at fire prevention and pre-planning. The National Fire Incident Reporting System (NFIRS) [11], an established information-gathering system, contains data that fire departments may be able to utilize and possibly could be a platform to be expanded upon specific to municipalities that are already participating. Some consideration to expanding the current NFIRS database system or developing a similar database along with improved access, possibly via cloud storage, should be considered. A lot of information goes into the NFIRS system, but the ability of field units to readily and timely access that information is lacking. Additional consideration should be given to developing a universal application software, or "app," that would allow access to the database. Access must be able to be achieved simply and efficiently by devices that are already used, universally accepted, and affordable, such as desktop computers, data terminal/computers on apparatus, notepads/tablet computers, and even smartphones. This would allow standardized, universal input of information as well as a simplified, affordable means of access.

The use of standard building codes and incorporating or identifying unique characteristics [e.g., heating, ventilation, and air-conditioning (HVAC) systems, sprinklers, and other fire suppression systems] as well as common fire potential issues (e.g., building construction, renovation, or deteriorating conditions) can assist fire departments in developing a nationally standardized, uniform approach to those problems. Identifying such issues within municipalities can also further identify the need for additional pre-planning and resources, possibly from neighboring fire departments. A universal database would mean that all responding fire departments can have access to the same information.

12.3.2 Responding

Real-time traffic patterns and delays, the best response route, the dimensions of the building associated with the address, and the height and size-up of the exposures are extremely critical pieces of information that could assist responding units. Such information might not be as critical for units that are normally "first due" and familiar with the address, but for units not familiar with response routes, for units responding from a distance or out of their area for mutual/automatic aid, for greater alarms, or for incidents requiring more resources, this information can be absolutely critical to a timely and efficient response by the resources and their operation. A universally acceptable, standardized, and simplified means of accessing information is critical. Interoperability has been identified as an issue not only for the fire service but for the various agencies that may be responding to an emergency. Interoperability is the ability of agencies to communicate, usually by radio, with each other. As technology advances and the need and availability of additional information and resources become available, they must also be universally accessible (see Figure 12.2).

Currently, responding units may rely on "route cards," paper maps, or pre-plan books that might contain relevant information. Frequently, though, much of this information is the knowledge that responders themselves possess. Certainly, up-to-the-minute traffic delays, possibly as a result of the incident itself, are not available. While GPS devices are becoming more commonplace, the time and attention to detail and steps required to enter the location prohibit the use and effectiveness of the device in this time-limited context. The delay in receiving information might in part be a result of signal restrictions due to high-rise buildings in an urban area or weather conditions, which frequently restrict delivery of the information in an accurate and timely fashion.

Although similar to a GPS system, one example of an information application that is timely, accurate, user friendly, and easily accessible is Google Maps [12]. Google Maps has the potential to be accessed directly from the apparatus by means of an onboard data terminal/computer or a handheld device such as a smartphone or notepad while responding to or returning from alarms, performing building inspections, or pre-fire planning. This simple app has the capability to provide the current location of the apparatus, street names, best route of travel, and traffic delays and can include satellite and three-dimensional building identification. Perhaps most important in a time-constrained situation, Google Maps can be utilized effectively with little or no user input.

12.3.3 Fire Fighting

New technologies are emerging and continue to be developed such as drones, and attempts are being made to integrate them into the fire service. Technological innovations applicable to the fire service include means for accountability, physiological monitoring, and situational awareness, to name a few. How much information is too much? What is a practical way to deliver the information and have it be relevant? Fire fighting can be subdivided into two or more categories or phases that operate as part of the fire-fighting scenario simultaneously. Depending on the specific agency, these phases generally can be classified as command, fire fighting, staging, overhaul, and rehab, and all can occur simultaneously at a fire, either structural or wildland, and at an incident.

Command is a function usually assumed by the ranking officer on scene, the incident commander (IC). The IC usually will establish a command post to oversee the incident a safe distance away from the hazard zone. At the command post, the

Figure 12.2 The cab of a fire truck. (Courtesy of Phoenix Fire Department.)

IC must attempt to maintain control and communications with all sectors of the incident. In the case of a high-rise fire, the command post might be located in the lobby, where all aspects of the buildings systems can be monitored while the actual fire fighting is many floors above the lobby command post. At most structural fires, the command post is usually located in front of the main entrance of the building; depending on the extent and the spread of the fire, the location and position of the command post can be relocated several times over the course of the incident. In the case of a wildland fire, not only might the command post be relocated over the course of the fire, frequently it is located miles away, either because of the magnitude of the fire or in anticipation of rapid fire spread and growth. In any situation, the IC might be assisted by other ranking officers and officials from several supporting agencies. The information they receive at the command post typically comes from several locations or sectors of the fire area or building, the incident dispatch center, and the supporting agencies. The command post must be responsible for defining the parameters of the incident, the position of the apparatus on scene, the staging, and the accountability of personnel on the scene. What is the exact location of the personnel — inside or outside the building? At a staging or holding area where additional resources are positioned? Or in a rehab area getting medically evaluated, having their vital signs monitored or bodily fluids replenished? Accountability is commonly accomplished by use of a command board that consists of a combination of tags, magnets, and grease pencils. The command board might also be equipped with additional radios (Figure 12.3). The information that the IC is required to receive and acknowledge includes radio transmissions from members and from sector commanders operating at the scene both inside and outside the hazard zone. This situational awareness (SA) or processing of information that must be updated periodically can be classified as conditions, actions, and needs (CAN):

- **C**onditions/progress or lack thereof: how are we doing?
- **A**ctions: what are we doing?
- **N**eeds: do we require additional resources for extinguishment or relief?

Figure 12.3 Fire command post. (Courtesy of FirefighterToolbox.com.)

The IC also has to maintain communication with a dispatch center that is constantly updating the command post on the duration of incident, weather conditions, and calls related to the incident such as from people trapped or in distress in the building or from people in the vicinity of the incident reporting smoke or spread of the fire. The dispatch center may also update the command post on the availability and status of additional resources. Generally, this information is conveyed via radio, and ICs frequently have to listen to more than one radio at a time. They might also receive information in the form of data via a data terminal in a vehicle or on a laptop, radio, or other device. The extent of the information can include the building construction; unique features, hazards, or alterations; and the contents of the building, especially hazardous materials. This information is critical to the success of the operation and, more important, to the safety of the fire fighters. It must be accurate and received simply in a standardized format and in a timely fashion, if not almost immediately.

As a rule, fire fighters on the fireground are already overworked due to personnel limitations that exist in both paid and volunteer settings and are tasked with carrying extreme amounts of weight. As already described, fully clothed structural fire fighters are usually wearing a PPE ensemble that consists of a coat, pants, boots, helmet, gloves, hood, and SCBA and carrying, at a minimum, a flashlight, portable radio, and a bail-out rope system. Frequently, they are carrying a thermal imager, hand tools such as an axe and/or Halligan tool, or a 6-foot-long pike pole, or they are dragging hose. They might also be carrying a power saw. In addition, they may equip themselves with miscellaneous items in their pockets. The total weight can be anywhere from 75 to 100 pounds or more of equipment (Figure 12.4). Questions that must be asked include not just what new technology can be introduced or integrated into the fire-fighting ensemble but what the additional weight factor is and, more important, what is its value. "Only another 3 pounds" adds up over the years as fire fighters are forced to carry more and more equipment the value of which is sometimes questionable — additional weight causes greater physical exertion on the part of the fire fighters, increasing the rate of fatigue. Consider another context for example, the emphasis that is placed on an individual who is involved in a weight loss program and gains 3 pounds.

Figure 12.4 Fire fighter in full gear. (Courtesy of Shutterstock.)

After getting adequate personnel to the scene, accountability for them is probably the number-one issue for any fire department. Over the years, the fire service has done a good job of developing simple ways of accounting for who is on the fireground or in the fire building, but does the IC know the exact location of the personnel? Tags on key rings or Velcro name tags on an accountability board at the command post or a "riding list" are means for fireground accountability, but they do not pinpoint where personnel are in the building. When members become lost or disoriented due to the building configuration or are trapped as a result of collapse or rapidly spreading fire, the question is not simply that they are not accounted for but more important exactly where are they? There are many documented instances of fire-fighter fatalities where fire fighters were lost or trapped and died before potential rescuers talking to them on the radio could determine their location [13].

While radio ID systems and other systems associated with the personal alarm safety system (PASS) [14] can be of some help, to date nothing is timely or three dimensional. Currently available systems tend to be unique to a manufacturer, thus limiting interoperability. Most of these devices utilize radio frequency (RF), which is extremely temperamental and not totally reliable, depending on the environment, building construction, and other factors. Product developers and manufacturers need to be less concerned with devices that are unique or proprietary to their interest and focus on what is useful and practical for all end users. Of paramount importance is standardization across the board from manufacturer to manufacturer — fire departments responding in other jurisdictions as partners in mutual aid agreements frequently find themselves utilizing different devices with no interoperability trying to accomplish the same goal [15]. New devices need a common operational platform — the reliability and simplicity of devices must be almost as universal and as simple as putting water on the fire. Water is supplied from various sources but ultimately it passes through a hose and is directed efficiently and effectively onto a fire. Putting water on a fire to extinguish it is a basic tenet of fire fighting that is accepted worldwide and that works in just about every instance of fire extinguishment.

Given that personnel availability is an issue, will one fire fighter be assigned to just monitor a screen for accountability? If only four or six members are placed on the fireground, does it make sense to have one of them utilized strictly for accountability? Should accountability take precedence over physiological monitoring systems? Who will monitor the fire fighters' physical status and how? What is the baseline? More important, will the monitoring technology just be additional weight for fire fighters to carry, causing them to exert more energy just so someone can notify them that they are overexerting themselves and need to leave the fire building? How beneficial is such information? Who will monitor it? At an incident, how much more information will ICs be capable of processing before experiencing information or cognitive overload?

12.4 Perceived Future Trends

The 2014 workshop "Visions 2025 — Interactions: Our Future with Social, Cognitive and Physical Intelligent Assistants" [15] projected that the interaction between people and computing will become a "multi-party people-to-machine interaction facilitated by immersive interaction with touch, gestures, speech, gaze, bio-data, facial expressions, object interaction, location, context, and more in a highly interconnected environment." Those interfaces and interaction paradigms have application and implications in the fire-fighting contexts of use as discussed in the following section.

12.4.1 New Interfaces and Interaction Paradigms

12.4.1.1 Voice/Speech Technology

In addition to voice activation for devices such as heads-up displays like "Google Glass" [16] or hands-free communication to smartphones, radios, and other devices, new speech and voice technologies could improve fire fighters' capabilities to communicate. Consider the use of speech recognition to improve fire fighter radio communication. Keyword extraction of fire fighter radio communication over the public safety network could be used to automatically display material on a map interface or to assist in the required manpower estimation [17].

NASA scientists are developing a subvocal speech recognition system that uses electrodes attached to the throat to detect biological signals that occur as a person reads or talks silently to himself or herself. The signals are then converted into text or synthesized speech. Since there is no requirement for sound, the technology eventually could be used for communication in high-noise environments such as the fire-fighting context [18].

12.4.1.2 Gesture

One could envision fire-fighting gloves instrumented for gesture recognition. For example, the iGlove, developed for DoD/NIH applications, detects individual motions of the fingers, hand, wrist, and arm. Current applications for the military include hand signal recognition and as a robot controller using the natural movements of the operator's hand/arm as the input device to control both the movement of a robot itself and the movement of ancillary devices such as grasping and lifting arms [19].

12.4.1.3 Eye Gaze

Traditionally, eye tracking has been used by website designers and marketing firms to determine the effectiveness of their products. Now the technology is being used to operate computers and wheelchairs, alert drowsy drivers, diagnose brain trauma, train machine operators, and provide surgeons with a "third hand" to control robotic equipment. But the technology has even more applications than controlling equipment. Consider the following examples that have applications in the fire-fighting environments. An eye-tracking scuba mask designed for Navy SEALs detects fatigue, levels of blood oxygen, and nitrogen narcosis, a form of inebriation experienced on deep dives. Software has been developed that determines whether circular or radial muscles in the iris are opening or closing the pupil. Radial muscles take over as stress and brain effort increase. Since a novice's brain works harder than an expert's to perform a given task, this provides a way to measure a person's level of expertise [20].

Several military applications use eye tracking. Flight instructors can use eye tracking to monitor the eye movements of pilots in flight simulators, which can determine if trainees are scanning gauges in the right sequence. Eye tracking could be used to aim weapons by ways of the wearer looking at a target, or control a small drone by an eye-tracking headset that can aim at whatever the wearer is looking at [16, 20, 21].

12.4.1.4 Immersive/Augmented Reality

Augmented reality (AR) involves the display of computer information as an overlay on the user's field of vision without the use of a fixed terminal or other traditional interactive display system. Consider, for example, the first down line projected on the television image during a football game. The fire fighting context could be another application. An AR system would allow fire fighters with head-mounted displays to interact with a computer using a virtual interface that is continually available in a nondisruptive manner, such as on the palm of a glove. This technology introduces significant opportunities for training by allowing three-dimensional representation of virtual environments, both for individual fire fighters in hostile environments and, on a larger scale, for ICs managing the fireground [22]. In a current prototype, an SCBA mask uses augmented reality, or synthetic vision, to display information to fire fighters through the mask. In this application, the mask shows fire fighters their oxygen levels and time remaining based on tank pressure and respiratory rate; the temperature and trend of the surrounding environment; exit paths and nearest egress points; "breadcrumb" paths of the steps the wearer has taken; the location of all other fire fighters on scene; a thermal-imaging overlay option triggered by a gesture interface; personal vitals; battery life of the radio; and the visuals of other team members [23].

12.4.1.5 Touch/Haptics

According to the dictionary, *haptics* relates to the sense of touch, to the perception and manipulation of objects using the senses of touch and proprioception. In regard to the discussion here, *haptics* refers to the tactile feedback technology designed to recreate the sense of touch to the user through forces, vibrations, or motions. Highly sophisticated touch technology can be found in industrial, military, and medical applications. A common application for haptics is training. Consider these examples: medical students practice surgical techniques on the computer, feeling what it's like to suture blood vessels or inject a serum into the muscle tissue of a virtual face; mechanics work with complex parts and practice servicing procedures, touching everything on the computer screen; soldiers learn how to defuse a bomb and how to operate sophisticated machinery, including helicopters, tanks, or fighter jets in virtual combat scenarios [24]. It is not difficult to envision haptic training scenarios for fire fighters, such as operating an aerial device or pumping water.

12.4.1.6 Wearable Computers, Electronic Textiles, and Bio-Sensors

Another application of technology relating to electronic safety equipment is electronic textiles, also known as e-textiles. This is based on microtechnology and nanotechnology that is introducing electronic wearable garments, with electronic capabilities built in the garment materials. They would function like other electronic safety equipment, with the ability to locally and remotely monitor environmental conditions, physiological conditions, tracking/location, and so on. Several variations are currently being looked at in the fire service. These include inner garments (t-shirt), outer garments (turnout coat), and even boots. Some have sensors attached to the garment, others have them embedded, and others include the sensors and the antenna woven into the material. Information gathered may be transmitted wirelessly to mobile phones, wrist-mounted devices, or to computers at a remote location.

A program that is directly addressing the physiological monitoring of fire fighters is the Physiological Health Assessment System for Emergency Responders (PHASER). This is independent of the electronic textiles efforts. PHASER involves the development of equipment that monitors a fire fighter's body temperature, blood pressure, and pulse, and transmits these back to the fireground incident commander [25–28].

12.4.1.7 Vibrations

Vibrations can be used to provide information and feedback to users. Consider "smart shoes," which vibrate or buzz when it is time to turn. In a challenging environment where it is difficult to see or easy to become confused or lost, having directions provided directly to the feet through the insoles of one's shoes, leaving the hands free, would seem to be an advantage [27, 29]. A second application is a tactile belt, which is under development for the military, that weighs only 0.8 pound and receives vibrations that can direct a soldier's movements without the platoon leader having to say anything [30].

Another team has developed a specially adapted tactile helmet that could provide fire fighters with clues about their surroundings. The helmet is fitted with a number of ultrasound sensors that detect the distances between the helmet and nearby walls or obstacles. The signals are transmitted to vibration pads attached to the inside of the helmet, touching the fire fighter's forehead [31].

12.4.1.8 Heads-Up Displays

A heads-up display (HUD) is any transparent display that presents data without requiring users to look away from their usual viewpoints. An example in the commercial market is Google Glass [16].

In the fire-fighting context, consider the new helmet design called the C-Thru. The C-Thru helmet integrates a number of functions, including thermal sensors and communication devices. A lead fire fighter with a C-Thru helmet will be able to look around with super-vision instead of constantly looking down at a hand-held thermal imager. The helmet will wirelessly transmit environmental and video data for processing. The processed information will then be distributed to all the team members and displayed on their HUD visors as a wireframe overlay of their surroundings. The U.S. Air Force currently employs a similar technology [32].

Other examples of HUDs include the U.S. Army's Smart Helmet [22] and the head-mounted display (HMD) AR technology of the proposed SCBA mask [23].

12.4.1.9 Context Aware/Location (Situational Awareness)

Context-aware computing is described as "a style of computing in which situational and environmental information about people, places and things is used to anticipate immediate needs and proactively offer enriched, situation-aware and usable content, functions and experiences" [33]. Studies have shown the need for fire fighters to exchange information about their situation and their surrounding environment. The constant movement of fire fighters in complex urban structures makes it difficult to maintain an always-on communication channel among them. Such interaction is especially useful when fire fighters need to be alerted about imminent dangers. An example of such an interactive device is small, cheap, wirelessly networked sensors that can be deployed on fire fighters and in buildings, capturing contextual information — temperature, sound, movement, toxicity, and a fire fighter's location. This type of information about the individual fire fighters and the environment can be relayed to all the fire fighters on scene to help improve safety and effectiveness. A demonstration system has been developed [34].

Wildland fire fighting presents challenges quite different from those encountered in structural fire fighting, the most obvious being the much larger geographical area. Recently a new system through the Fire Line Advanced Situational Awareness for Handhelds (FLASH) program was tested for fire fighters battling wildfires. The prototype system included tablet computers, aircraft-mounted sensors, and radios designed to identify the location of every fire fighter and fire-fighting aircraft in expansive fire zones. The system overlaid multiple streams of information from airborne sensors, fire fighters, and fire command posts onto a shared digital map visible on tablet computers. Fire fighters and ICs were able to track each other's positions in real time, monitor the position of an observation aircraft overhead, and watch a live-video feed from the aircraft that provided a bird's-eye view of the terrain. Participants in a command post and in remote areas viewed the same live video feeds from the aircraft and communicated in real time with fire fighters in the field. The FLASH system relies in part on Mobile Ad Hoc Networking (MANET) radio technology. Although not yet fully developed, FLASH has great potential to increase situational awareness as well as personnel accountability, two items paramount to a successful and safe wildfire operation [22].

12.4.1.10 Mobile Devices

As devices of all kinds get smaller and "smarter," they will have more and more potential applications for training, accountability, physiological monitoring, communicating, and more in the three contexts of use — office/fire station, responding, or fire fighting.

12.4.2 Barriers to Technology Development and Adoption

12.4.2.1 Cognitive Overload, Alert Fatigue, and Competition for the User's Attention

What had once seemed like futuristic technological developments are rapidly emerging. Equipment that is now commonplace for fire fighters includes thermal imaging cameras, hazardous gas analyzers, video cameras, and even HUD units within an SCBA. New technologies such as position-locating/tracking devices, HMD-AR, environmental sensors, physiological monitors, and electronic textiles are quickly becoming a reality. The human brain has finite resources, yet all this technology is competing for limited attention by the user, not only the fire fighter wearing the electronic equipment but also incident command receiving information from multiple fire fighters.

Too many interfaces or inputs requiring user attention can result in cognitive overload. Cognitive psychology suggests that the amount of information and interactions that must be processed simultaneously during complex activities can overload one's finite amount of working memory. Cognitive overload was one contributing factor to the problem in the Three Mile Island nuclear disaster. Users simply do not have the capacity to simultaneously process a large number of competing inputs from multiple interfaces. Designs must minimize the cognitive load.

In addition to cognitive overload, alert fatigue arises when numerous different systems — from radios to physiological monitoring devices to SCBA masks — give prompts, alerts, or alarms, to which the fire fighter no longer pays attention. A similar phenomenon in the medical community has been described as a digital version of "the boy who cried wolf" [35, 36]. Ignoring alerts and relying on one's own judgment is of concern because many alerts are designed to prevent errors or serious exposure. Again, designs must minimize alerts and alarms and allow for the categorization and prioritization of information.

12.4.2.2 System versus Component View

While all the interfaces and interaction paradigms discussed here can be partnered with sensors and other technologies to potentially address fire service problems and needs and improve performance and safety, this cannot be done in a vacuum. Consider, for example, the following analogy. The SCBA is often referred to as a "Christmas tree," meaning innovators and manufacturers alike are looking to "hang" more features and devices on it. Currently SCBA users receive information from devices attached to the unit, including an end-of-service time indicator (EOSTI), which alerts the user visually, audibly, or both that the reserve air supply is being utilized, and a HUD that can include both visual alert signals and visual information displays. Another audible indicator is a PASS device [14]. Additional devices incur transmission and reception of new information, require additional power to function, add weight, and raise interoperability concerns. All these factors must be evaluated in context. Designing components and devices in isolation without consideration of proper integration, interoperability, and interdependences will result in cognitive overload, sensory interference, and alert fatigue. While a product may be developed with the best of intentions, its usefulness will be compromised if there is a lack of attention to proper integration.

To truly address fire fighting and provide fire fighters with the right information at the right time and delivered in the right way so they can make the right decision, research and development of devices must take a whole-system approach rather than a piecemeal, or component-oriented approach. The NFPA standards that govern PPE and SCBA (NFPA 1971, *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* [5], and NFPA 1981, *Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services* [6]) do not require a system perspective or systems-level approach — any addition to PPE or SCBA or integration into them requires a revision of the standard.

12.4.2.3 Interoperability and Integration

Manufacturers must be extremely mindful of the regulations and specifications regarding existing systems and the reactionary challenges that might arise when they attempt any integration of new technology into an existing system. One example is fire apparatus. The desire or need for more capabilities lends itself to complications. Systems include onboard computers to govern emissions, the shifting capabilities of transmissions, the engine speed, and function. The electronics and sensors required to perform the monitoring as well the electrical power requirements for those systems, for lighting, and for communications systems have all complicated newer apparatus to the point where they have become almost counterproductive with regard to efficiency and cost. In many instances, "better than" is the enemy of "good enough" [37]. The many complicated systems and lack of proper interoperability seem to lead to more and more of the newer apparatus being out of service more than in service, with mechanics and technicians unable to properly diagnose and repair the issues. The attitude of "let's try this and see if it fixes the problem" is becoming more the norm than the exception; frequently the quick-fix solution leads to additional issues that prove to be more difficult or more expensive (sometimes both) to correct. Ultimately for every action there is a reaction, and "more stuff" leads to more problems, especially where electronics are involved. All too often, systems are not beta tested long enough in a variety of conditions and wear scenarios to produce a stable, reliable system that will properly interface with other components in a variety of design interfaces. In the case of fire fighters and fire trucks, "more stuff" usually means more weight, which requires a stronger foundation (fire fighter or fire truck) as well as a greater need for proper interoperability.

12.4.2.4 User-Centered Design

A holistic approach adhering to user-centered design principles, including extensive usability testing and standards, is necessary to address fire fighters' concerns. From the literature review, it appears that most fire-fighting technologies and devices are tested, measured, and reported independently of human factors, including the user. The user must be viewed as an interactive and integrated component of the fire-fighting system. Consider the case of a device of significant weight added to the PPE or SCBA. How does the additional weight affect fire fighter performance, efficiency, and effectiveness? The human factors and users' behaviors must be considered as part of the system to truly measure overall system performance. To improve the performance of these technologies, it is critical to take a systems approach that integrates the needs of users as well as the entire experience users will have with the hardware, software, and other components of a system. Adopting a systems view that includes the user in the process is not only beneficial to the end users but also can help improve the performance and effectiveness of the overall system and the outcomes.

Consider a thermal imaging device developed to be attached to a fire fighter's helmet. Although the use of thermal imaging technology has proved to be beneficial, the integration was not thoroughly thought through prior to the product being brought to market. When a training component was developed to instruct fire fighters in the proper use of the thermal imager, it was determined that there were severe shortcomings in the attachment and integration of the device to the fire helmet. The device was held in place with a band that wrapped around the shell of the helmet. When a fire fighter removed his or her helmet and placed it upside down while donning the SCBA facepiece, the band around the shell would slip off the helmet, separating the device from the helmet. The manufacturer's temporary fix was to use binder clips from an office supply store to secure the band to the helmet brim. The fix worked temporarily, but the design shortcoming could have been identified and properly addressed in the beginning had the manufacturer been more diligent and taken a holistic system and user-centered view rather than an individual component view to address interoperability and integration. Additional consideration also should have been given to product standards and certification for fire fighters' helmets and how any modification to the helmet, such as adding the thermal imager, could negate that certification.

Although there is a substantial body of knowledge and research regarding user-centered design and usability principles, much of this information is not yet integrated into the standard design and development processes of today's fire-fighting systems. Fire fighters must be involved in defining the requirements, the design solution, and especially the testing.

12.4.2.5 Need for New Standards

Current NFPA standards for items such as PPE and SCBA set forth minimum performance criteria to which items are tested in order to achieve certification. It can be assumed that future devices also will be required to meet the requirements of those standards, especially when integrated into a current device. Most of the tests are relevant to the performance of the device or equipment in the environment it is intended to be used, the harshest being fire. The old adage of a chain being only as strong as its weakest link holds true of a device that is developed and deemed useful but is not capable of withstanding the environment. It is becoming more apparent that all the components of an ensemble must be designed and built to operate together and to withstand the same environments.

Over the past few years, there have been several examples of devices or components of devices that have failed despite having been certified as compliant to an NFPA standard. Despite the rigid NFPA standards being in place, devices are only as strong as their weakest component. These failures have been identified as a result of fire fighter line-of-duty death investigations conducted by the National Institute of Occupational Safety and Health (NIOSH) Fire Fighter Fatality Investigation and Prevention Program or FFFIPP. Examples of failures identified by the FFFIPP include failures in the PASS device when exposed to high heat and water. More recently, failures were identified in the SCBA facepieces exposed to high heat despite the fact that the rest of the ensembles survived. Currently the NFPA Technical Committee for Electronic Safety Equipment is working on the proposed standard NFPA 1802, *Standard on Personal Portable (Hand-Held) Two-Way Radio Communications Devices for Use by Emergency Services Personnel in the Hazard Zone*. The FFFIPP investigators also have uncovered deficiencies in portable radios used by fire fighters when exposed to heat. The portable radio is considered a life safety device for fire fighters. There are three different temperature thresholds for the three main components that make up a fire fighter's portable radio: the radio itself, the remote speaker microphone, and the cord that connects the two. The temperature thresholds for each of the three components is far below the acceptable temperature limits set for the rest of the equipment utilized in fire fighters' PPE ensembles.

While NFPA standards are not mandatory unless enacted into law by a jurisdiction, they represent some form of standardization and reliability to the fire service and ultimately are the benchmark against which a fire department is held accountable in the instance of a fire fighter's death or injury.

Standards and the development of new devices should include **user testing** (usability testing) to determine the efficiency, effectiveness, and safety of the devices and their interfaces in the varied contexts of use.

12.4.3 Challenges of New Interfaces and Interaction Paradigms

The fire service is frequently referred to as "bottom feeders" due to the fact that the devices and technology introduced as being beneficial are designed for other more financially lucrative industries or organizations, such as the military. As a result, what the fire service ends up with is something designed for another application and not specifically designed for the challenging environments of fire fighting. While technology transfer from other disciplines and services can be extremely beneficial, new devices must be developed specifically for their intended use and operational environment. There are examples where devices built to military specifications often do not withstand the rigors of fire fighting. This only emphasizes the need for user-centered design and fire fighters' participation in the requirements definition, design, and user testing of new technologies in the appropriate contexts of use.

A final challenge is user acceptance. User acceptance is predicated on many factors, including all the barriers identified here. But ultimately the device, technology, or system must address a specific task identified by the fire fighter and result in improved efficiency and effectiveness for the fire fighter and provide some level of satisfaction in the fire fighter's context of use. Simply put, it must be usable.

12.5 Technology Gaps

While there are admittedly technology gaps facing Smart Fire Fighting, there are also existing research methodologies appropriate for addressing those gaps with respect to competition for users' attention, cognitive overload, and alert fatigue as well as other human performance characteristics. There is a rich existing literature base of human cognition and performance from which to draw; while it may not be tailored specifically to the fire fighters' task environment(s), it nonetheless should serve as a valuable starting point and save researchers in the fire-fighting field from reinventing the wheel where human cognition research is concerned. Given its predictive power, human performance modeling, such as computational cognitive modeling, is of particular interest for researching the technology gap in fire fighting, as well as any domain in which access to subject matter experts in realistic scenarios is difficult or dangerous, such as aviation.

The modeling community can contribute much in the way of both basic and applied research relevant for fire fighting, such as research on language processing, memory, attention and perception, problem solving and **decision making**, workload, multitasking, spatial reasoning and navigation, situational awareness and embedded cognition, and skill acquisition. (For a more complete listing of modeling research areas, see the ACT-R publication website, http://act-r.psy.cmu.edu/publication/.) Furthermore, modelers are researching the effects of stress, sleep loss, and caffeine on cognition and performance. Although an in-depth literature review is out of scope for this section, the following noninclusive references clearly illustrate the potential relevance of existing modeling literature and methodology:

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12.6 Perceived Priorities for Research

If Smart Fire Fighting technologies are to be successful, fire fighters must be able to achieve specified goals simply and with effectiveness, efficiency, and satisfaction in a specified context of use, in other words, the technologies must be usable. The following three priorities are critical to successful interfaces in Smart Fire Fighting technologies:

1. The application of the human-centered design approach to the technology development to fully understand fire fighters' needs, their tasks, and the context of use. Fire fighters must be part of the development process from the beginning.
2. Research and development of devices must take a holistic system view rather than an individual component view to better address interoperability and integration.
3. Extensive usability and beta testing to include every intended context and task repeatedly over time using ISO/IEC 25062:2006 to document the testing results in the Common Industry Format for complete documentation and comparison of testing results.

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SECTION

3

CONCLUSION

CHAPTER 13

Core Chapter Observations

Casey Grant

Fire Protection Research Foundation
Quincy, MA

13.1 Introduction

This research roadmap presents a series of needs prioritized to advance Smart Fire Fighting. The priorities have been distilled from research recommendations collected through a number of mechanisms. This includes the Smart Fire Fighting Workshop [1], the coordinated efforts of each core chapter team, a Chapter Authors Review Meeting (held November 4, 2014, in Arlington, VA), feedback from multiple presentations on this topic during the course of the project, and assorted additional input.

In addition to identifying key research priorities, the chapter-author teams were asked to address additional issues for the material associated with the core chapters, including the following:

- Review of existing and available knowledge and technology
- What is needed in terms of technology or tools
- What knowledge (and/or technology) is needed
- Other pertinent information

The information presented by each chapter-author team was collectively reviewed by all the authors in detail and discussed at the chapter authors meeting. This chapter summarizes the perceived research gaps as provided by each of the author teams for each core chapter of the research roadmap.

13.2 Research Priorities for Communications Technology and Delivery Methods (Chapter 2)

Chapter 2, Communications Technology and Delivery Methods, focused on the gathering of data based on communications technology and delivery methods, including personal area networks on-board fire fighters, teams and units, fireground incident command, and inter-jurisdiction.

The following are the top research priorities presented in Chapter 2:

a) *Assessment of Traditional Communications Infrastructure*. Clarify if traditional communication infrastructure is appropriate for fireground applications.
   - Survivability (e.g., reliability, durability, maintainability)
   - Operability
   - Extensibility (i.e., the need to have converged devices to support both mission critical voice and mission critical data)
   - Other critical issues addressed by national and international initiatives (e.g., FirstNet)

b) *Holistic Interoperability*. Focus on single-system interoperability.
- Where? What? How? (e.g., RF, spectrum, bandwidth)
- Demonstrate operability via continual external use (i.e., trustworthiness)
- Heterogeneous networks (e.g., a mix of macro-cell, pico-cell, WiFi, etc.)
- Device-to-device (d2d) networking (e.g., mobile phones talking directly to each other independent of supporting infrastructure)

13.3 Research Priorities for Sensors as Part of Personal Protective Equipment (Chapter 3)

Chapter 3, Sensors as Part of Personal Protective Equipment, addressed sensor technology involving personal protective equipment (PPE), that is, fire fighter on-board electronic safety equipment (ESE) that includes but is not limited to environmental monitoring, physiological monitoring, sensory support, tracking/location, and electronic textiles.

The summary discussion for PPE sensors included the following highlights:

- Fire fighters are subject to a number of physical and environmental hazards grouped into four general categories: (1) thermal and radiative, (2) structural collapse and physical injury, (3) chemical and particulate aerosols, and (4) acoustic.
- Sensors embedded in PPE can provide a variety of useful functions: (1) environmental assessment to ensure personal safety, (2) facilitation of real-time decision making by incident commanders, and (3) increase of fundamental knowledge on risk factors and long-term exposure outcomes.
- The general sensor categories are (1) environmental, (2) biometric, and (3) geophysical tracking and location.
- Although we are living in a technology-rich environment, focused developments are required to produce practical end-use sensors and systems.
- PPE sensors are critically dependent on other system provisions, for example, data logging, communications, and interoperability standards and protocols.

The following are the top research priorities presented in Chapter 3 and discussed collectively by the core chapter authors:

a) *Environmental Sensor Technology*. Focused development of selected sensor types, possibly targeting chemical and particulate aerosols, biometric assessment, and geophysical tracking. Features to emphasize include species selectivity, size, mass, power consumption, durability, and cost (short term).

b) *Sensor Systems*. PPE sensors must be viewed on a system level, in particular with respect to data logging, communication, and operational protocols (short and long term).

c) *Implementation Factors*. Wider dissemination of sensors into the fire-fighting environment is and will continue to be paced by interoperability, ease of use and maintenance, and overall cost (short and long term).

13.4 Research Priorities for Mobile Sensors (Chapter 4)

Chapter 4, Mobile Sensors, addressed sensor technology involving mobile fire fighting, including but not limited to portable equipment (mobile equipment not on-board the fire fighter), land-based vehicles' air and water craft, robotics, and UAV/satellites.

The summary discussion for Chapter 4 included the following highlights:

- Scope: portable equipment, land based vehicles, air and water crafts, unmanned vehicles, robotics
- Cross-cutting concern of remote data communications and the application stack: RF issues, bandwidth, reliability, interoperability, apps environment

- Short term (up to 3 years): Use of telematics, remote sensing, unmanned vehicles, and integrating sensing and remote communications
- Medium term (3–6 years)
  - Adding additional sensors and improved hardening and reliability of the platforms
  - Increased RF interoperability for plug-and-play of equipment from disparate sources
- Long term (beyond 6 years): Humanoid robotics and expansion of autonomous fire fighting, search-and-rescue apparatus.

The following are the top research priorities presented for Chapter 4 and discussed collectively by the core chapter authors:

a) *Standardization*. Ontologies and data standards specific to portable data equipment to enhance incident command (short term)

b) *Mobile Network Integration*. Integration of reliable RF and mobile networking technologies with portable equipment (medium term)

c) *Mobile Robotic Sensors*. Autonomous/swarming UAV/robotics (medium to long term). For additional details, see Figure 13.1.

Figure 13.1 Detailed recommended research priorities for mobile sensors.

Area	Research	Barriers	Impacts of Success
Portable equipment	1. Define data needs from portable equipment to enhance incident command (driven from incident command — not equipment) 2. Develop and test communication protocol for high-priority equipment	1. Incident command needs	1. More robust incident command decisions based on more and better data
Land-based vehicles	1. Driver health monitoring 2. Crash avoidance 3. Sensors, communication, and control between 'end of hose' and pump control and related functions	1. Data communications and costs 2. Cost	1. Fewer deaths and injuries to fire fighters and other emergency responders in route to incidents 2. Same as 1 3. More immediate response of water needs at the nozzle — better pump control
Air and water craft			
Unmanned vehicles	1. Autonomous/swarming UAVs 2. Resilient sensor platforms for harsh environments 3. Robust mobile communications technology	1. FAA — autonomous navigation — environmental resilience — monitoring, command, and control systems — cost 2. Cost	1. Fewer fire ground deaths and injuries
Robotics	1. Autonomous/swarming robots 2. Walking, grasping, human-like robots 3. Resilient sensor platforms for harsh environments 4. Robust mobile communications technology	1. Autonomous navigation — environmental resilience — monitoring, command, and control systems — cost 2. Fine motor controls — cost 3. Cost	1. Fewer fire ground deaths and injuries
Remote data communications	1. Developing reliable and interoperable radio links for data exchanges		1. High reliability and high availability of Smart Fire Fighting distributed Cyber Physical System
Application architectures	1. Developing sensor services ontologies 2. Developing middleware to support ecosystem of apps developers	1. Industry alignment 2. Bootstrapping	1. Supplier diversity and innovative and feature rich applications that enable Smart Fire Fighting

13.5 Research Priorities for Stationary Sensors (Chapter 5)

Chapter 5, Stationary Sensors, addressed sensor technology involving stationary technology, including buildings, occupants and the general public, public and utility services infrastructure, and the outdoors.

The summary discussion for Chapter 5 included the following highlights:

- Stationary sensors are powerful sources of information for the following reasons:
  - They exist on-scene without fire fighting carriage or deployment.
  - They provide information throughout the timeline of an incident, for example, pre-planning inspection, incident, investigation, and forensics.
- Existing technologies for building systems and occupant sensing are established and broadly distributed but they are not specific to fire or integrated with the proper context for Smart Fire Fighting.
- The use of stationary sensors in Smart Fire Fighting would require the following:
  - Improved integration (security and trustworthiness) for emergency responders to integrate with private buildings and occupants
  - Synchronization with occupant-carried sensors, with daily lives and activities to minimize cost, training, and initiation time

The following are the top research priorities presented in Chapter 5 and discussed collectively by the core chapter authors:

a) *Building information modeling (BIM)*. Fully implement BIM framework to contextualize stationary sensor network

b) *Emergency Communication Protocols*. Establish privacy, security, trustworthy, seamless emergency protocols between the fire service and stationary sensor networks.

c) *Human Sensing Technologies*. Seamlessly synchronize important new human sensing technologies into the daily lives of occupants.

13.6 Research Priorities for Data Collections (Chapter 6)

Chapter 6, Data Collections, addressed existing database collections (e.g., fire loss records, fire fighting resources, building information modeling, building supporting infrastructure, the outdoors), as well as trends for future databases.

The summary discussion for Chapter 6 included the following highlights:

- The guiding principles of response are used:
  - Planning: capability assessment, vulnerability/risk assessment, inspections
  - Preparedness: pre-incident planning, resource deployment, training and exercises
  - Responses: CAD, AVL, and routing; in-vehicle applications; mobile/field intelligence; search and rescue; evacuation/shelter/mass care; public warning and notification; multidisciplinary coordination; and operations dashboard
  - Recovery: damage assessment, debris removal, infrastructure restoration, economic and community recovery, environmental stabilization, public information, analysis and management of recovery efforts
- Consider existing national data collection systems (e.g., NFIRS, NEMSIS, N-FORS, BATS)
- Going forward, data that are unified and scalable, in a system of systems, will be required
- Consider four separate data systems, based on each guiding principle:
  - To cover different aspects of emergency systems
  - To acknowledge the burden on emergency personnel to learn multiple systems

- Needs include the following:
  - Standardizing back-end systems and user interfaces
  - Automating use of sensors
  - Lowering costs using consumer mobile devices
  - Providing common set of tools to create content using domain expertise from various agencies

The following are the top research priorities presented in Chapter 6 and discussed collectively by the core chapter authors:

a) *Virtual Environment Center of Excellence*. Operating a "center of excellence" or " fusion center" for each of the guiding principles of response established and structured in the "virtual environment" is a must if the utilization of advancement from the universe of response elements is going to advance in a cohesive manner. Having a center for each segment (planning, response, preparedness, and recovery) and the associated communities would allow for cross fertilization and best practices to proliferate. Suggest that a test center be designed and operated as a research project. This is a long-term priority.

b) *Data Collection Cloud*. Establish a research effort to "cloud" specific elements of the data collection for response. This cloud would be researched and developed in such a manner that it would drive forward topics that support a particular effort (e.g., residential fire safety) such as the national reporting on the activation of smoke detectors in residential fires and the elements of that activation (e.g., battery operated or hard wired). This is a short-term priority.

c) *Graphic Interface System (GIS) Tools*. Clarify the usage and trends of GIS "framework" tools used by communities today. With the investment on the next generation of CAD ("smart CAD") currently underway, research which elements are being utilized, how the investment has benefited the communities that expended the funds, and ways to quantify the return on investment. This is a short-term priority.

13.7 Research Priorities for Hardware/Software (Chapter 7)

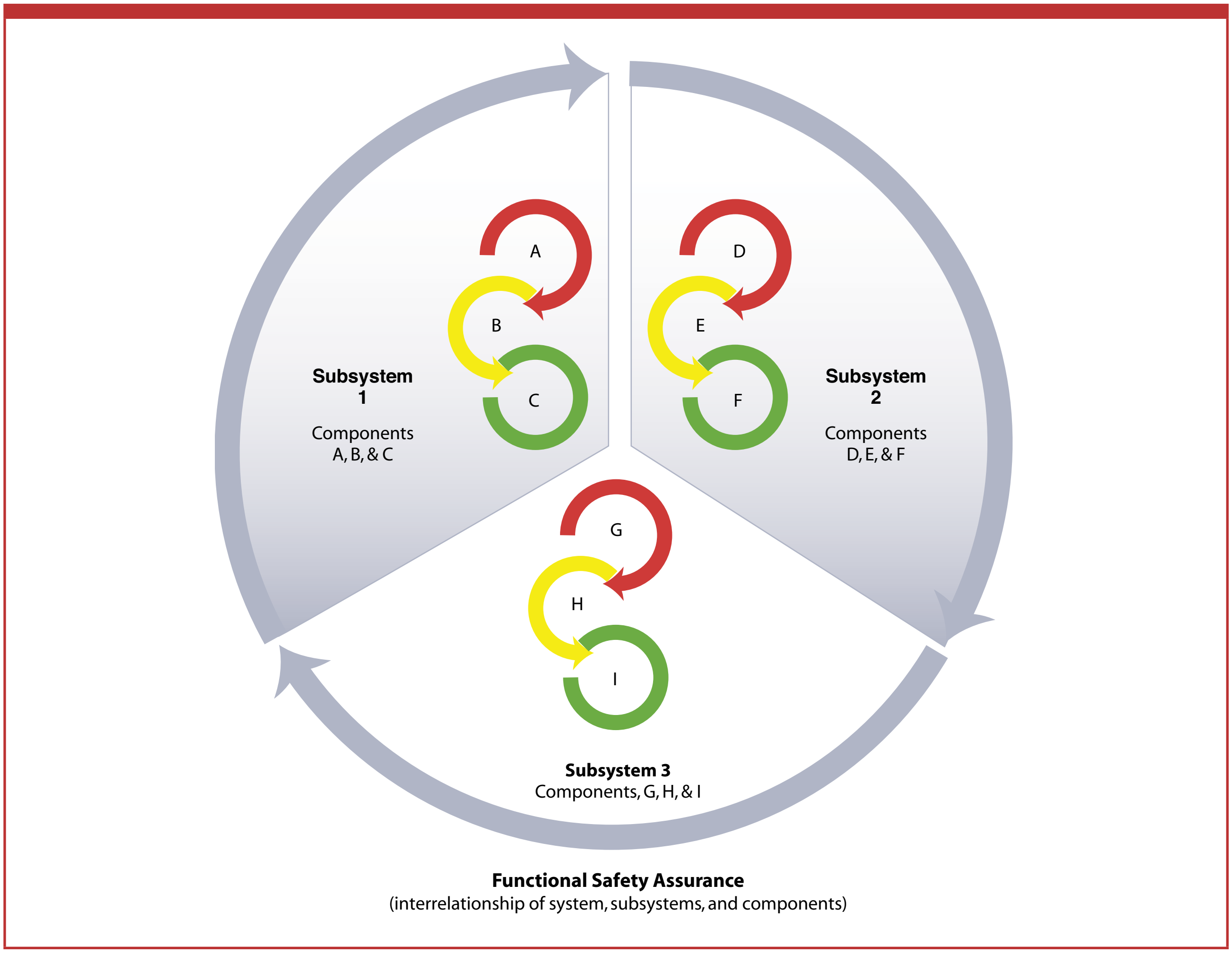
Chapter 7, Hardware/Software, addressed the computation of data involving hardware and software, including issues relating to compatibility, integration, and interoperability.

The following are the top research priorities presented in Chapter 7:

a) *Functional Safety Assurance*. Seamless and smooth functionality requires that, for any given system, all involved subsystems and components have full interoperability and that concerns for final intended function have been fully mitigated. Complete scalability is required to confirm proper function of all hardware and software. Two issues serve to limit the scale for specifying interoperability of the fire-fighting hardware and software, including the need to collectively identify the subsystems and components in any given system and the need to reconcile the overall performance of the entire system with the performance of any particular subsystem and component. For example, the process by which systems are tested and certified to specific standards (NFPA, NIOSH, ASTM, etc.) sometimes applies to a complete system and as a result challenges further division of the scale, while in some other cases the process applies only to individual components. This process requires the system — complete with any accessories — to operate as a whole entity. If someone replaced a subsystem, component, or accessory, then generally speaking, the system would no longer be certified to the particular standard. Such action could potentially lead to product liability and possible legal action if an injury occurred to a fire fighter using the particular system; legal ramifications would apply not only to the person or company who made the replacement or attached the accessory but possibly also to the jurisdictional authority that allowed the modification. The interrelationship needed to obtain functional safety assurance is illustrated in Figure 13.2, symbolizing the interrelationship of three distinct subsystems (with components A/B/C, D/E/F, and G/H/I) in a single overall system.

b) *Simulation*. The proliferation of simulation constitutes a tremendous opportunity not only to educate and train emergency responders but just as important to educate society on field operations and similar critical activities.

Figure 13.2 Interrelationship in support of functional safety assurance.



Using simulation in a realistic virtual world as a mass-scale information provider opens up the area of so-called designers and others are given the tools to actually act and improve field operations whenever such an improvement is required and desired.

c) *Widespread Implementation*. The optimum business models to support the proliferation of technology and widespread implementation of concepts supporting Smart Fire Fighting must be clarified. Enabling widespread implementation requires understanding and support of marketplace policies for the Smart Fire Fighting arena. This will need to coordinate with existing marketplace activity, which in some cases is already well established.

13.8 Research Prioroties for Real-Time Data Analytics (Chapter 8)

Chapter 8, Real-Time Data Analytics, addressed real-time data analytics such as data mining and big data applications, as well as knowledge-based fire fighter decision making and analysis (e.g., risk a little to save a little versus risk a lot to save a lot), such as modeling, inverse modeling/data assimilation, algorithms, and database analytics.

The summary discussion for Chapter 8 included the following highlights:

- A useful and informative review of existing knowledge and technology on this topic provided by *NIST Technical Note 1780* [2]
- What is needed
  - Smart sensors for CO, smoke, and heat
  - Reliability of the sensors and trust in them by fire fighters
  - Systems model for federal, state, local, and global stakeholders
- Knowledge that is needed: knowledge about human cognition, behavior, performance (particularly when under "fire"), and for all elements of society
- Education: learning at all levels, including at key doctoral–ranting institutions

The following are the top research priorities presented in Chapter 8 and discussed collectively by the core chapter authors:

a) *Model Deployment*. Deployment of the successful data analytics models to three major cities in the United States (<3 years) and globally (>3 years)

b) *Sensor Standardization*. Deployment of data-dependent performance-based codes and standards for environmental sensors (one major U.S. city in <3 years) and most major global cities (>3 years)

13.9 Research Priorities for Fire Service Data User Applications — Pre-Emergency and Post-Event (Chapter 9)

Chapter 9, Fire Service Data User Applications — Pre-Emergency and Post-Event, addressed fire service data user applications focused on the pre-event and the post-event, including but not limited to inspectors and enforcers, pre-planning, training and education, and fire investigation.

The summary discussion for Chapter 9 included the following highlights:

- Data leads to information, which leads to knowledge.
- Current technology is largely based on hard-copy forms for both the pre-event and the post-event.
- Huge advances are possible with digitized data forms directly linked to databases.
- Tools to "mine" databases need to be developed.
- A huge potential exists to collect data in our sensor-rich world, for example, digitization of homes and structures via smoke alarms and security systems.
- Social media need to be utilized as a tool, including as a source of data that can be mined and utilized.

The following are the top research priorities presented for in Chapter 9 and discussed collectively by the core chapter authors:

a) *Digitizing Existing Databases*. Digitization of hard-copy data forms linked to a common database format (time frame: 3–5 years)

b) *Database Adaptation*. Database format with tools to reformat data into information and knowledge (time frame: 3 years)

c) *Data Format Normalization*. Normalization of data format, including device clocks (time frame: >3 years)

13.10 Research Priorities for Use of Data During an Emergency Event (Chapter 10)

Chapter 10, Use of Data During an Emergency Event, addressed fire service data user applications focused on the fireground and emergency events, including but not limited to buildings, transportation systems, wildland, and special applications (proximity, technical rescue, hazmat, EMS, etc.).

The summary discussion for Chapter 10 included the following highlights:

- Off-the-shelf products and systems can be leveraged effectively to keep up with demand.
  - New upcoming sensing and networking technologies can be very useful.
  - Use static sources of information (e.g., GIS) as well as dynamic sources (changing conditions as identified by in-situ and mobile sensors).
  - Technology use requires adequate training and determination of how it affects a delineated process.
- Correct identification of data sources, how to access them, and mechanisms for the integration of multiple types of information are needed to push the right information to incident commanders (and other identified stakeholders) at the right time.
  - Different stakeholders have different tasks and require raw data/information processed in different ways.
- Improvements are required in system dependability, stability, and rapid setup of capture and communication infrastructure; interoperability is required at multiple levels — data, network, device. Network security and trust/confidence may be of greater concern in some situations.

The following are the top research priorities presented in Chapter 10 and discussed collectively by the core chapter authors:

a) *Operational Dependability*. Device, network, and communication dependability and stability

b) *Operational Security*. Confidence and security of end-to-end operation:
- Environmental protection of hardware and systems
- Trustworthiness of information from sensors

c) *Situational Awareness*. Situational awareness systems:
- Necessary for task saturation mitigation
- Seamless integration of infrastructure and analytics in a dynamic manner based on what is available (locally, regionally, and in the cloud)
- Design of easy-to-use interfaces (GUIs, speech-based interaction), dashboards, and mobile apps.

13.11 Research Priorities for Non–Fire Fighter Data User Applications (Chapter 11)

Chapter 11, Non–Fire Fighter Data User Applications, addressed the user applications that involve data for other than fire fighters, such as call processing centers (e.g., 9-1-1 centers), primary and secondary emergency receivers (e.g., hospitals, medical examiners, environmental cleanup, salvage, insurance), general public and building occupants, and governmental administration.

The summary discussion for Chapter 11 included the following initial highlights:

- Next-generation 9-1-1 and automated alarms
- Emergency medical receivers
- Mass notifications and IPAWS-OPEN
- How to alert specific relevant areas and groups, without “crying wolf”
- Emergency assistance applications
- Intelligent transportation routing and signage
- Risk-based building inspections

The following are the top research priorities presented for Chapter 11 and discussed collectively by the core chapter authors:

a) *Data Interface Emergency Access*. Exposing building data to fire fighters, as well as civilians, during emergencies through a "Knox Box-like interface."

b) *Civilian Interfaces*. Enabling user and civilian interfaces that are easy to use, are personalized, provide critical information, and remain navigable in stressful situations.

c) *Transportation Routing and Signage*. Provide flexible digital signage that adapts to emergency situations to create a "living" transit/transportation system.

13.12 Research Priorities for User Interface Delivery Methods (Chapter 12)

Chapter 12, User Interface Delivery Methods, addressed the delivery methods for user interfaces such as hand-held devices, heads-up displays, and augmented reality.

The summary discussion for Chapter 12 included the following highlights:

- Usability is defined as the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use. Usability must be a prime consideration if user interface delivery methods are to be successful. It is critical that fire fighters receive the right information/data at the right time, delivered in the right way in order to make the right decision.
- The definition of usability focuses on three primary components: users, users' goals/tasks, and the users' context of use. This chapter defined three contexts of use for fire fighters: (1) office/stations, (2) context of responding, and (3) fire fighting (i.e., operations).
- Interface and interaction paradigms examined in the fire-fighting contexts include:
  - Voice/speech technology
  - Gesture
  - Eye gaze
  - Immersive and augmented reality
  - Touch/haptics
  - Wearable computer and electronic textiles/biosensors
  - Vibrations
  - Heads-up displays
  - Context awareness/location (situational awareness)
  - Mobile devices
- Barriers to technology development and adoption include:
  - Competition for the user's attention, cognitive overload, and alert fatigue
  - System versus component view
  - Interoperability and integration
  - A focus on user-centered design and usability principles
  - The need for new standards

- Challenges
  - Technology transfer of systems and components
  - User acceptance
- Technology gaps
  - Computational cognitive modeling

The following are the top research priorities presented for Chapter 12 and discussed collectively by the core chapter authors:

a) *Human-Centered Design*. Implement human-centered design as an inherent part of all technology development.

b) *System Holistic View*. Utilize a system holistic view rather than an individual component view to better address interoperability and integration.

c) *Testing Protocol*. Establish extensive usability and beta testing to include every intended system repeatedly over time.

13.13 References

1. Grant, Hamins, Bryner, Jones, Koepeke, and Anand, 2014. *NIST Special Publication 1174: Smart Firefighting Workshop Summary Report.* Gaithersburg, MD: National Institute of Standards and Technology.
2. Reneke, P. A., 2013. *NIST Technical Note 1780: Towards Smart Fire Panels.* Gaithersburg, MD: National Institute of Standards and Technology.

CHAPTER 14

Summary Observations and Recommendations

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14.1 Introduction

The purpose of this research roadmap is to identify and prioritize the research and development needs for implementation of the next generation of smart systems to benefit fire protection and fire fighting. The idea of Smart Fire Fighting is outlined in Chapter 1 of the roadmap and is based on creating, storing, exchanging, analyzing, and integrating information from a wide range of databases and sensor networks. There are many challenges that must be overcome to exploit the promise of smart technologies as outlined in Chapters 2 through 12. This chapter summarizes key research priorities.

Throughout this study, there have been a multitude of recommendations for future research in support of Smart Fire Fighting. This chapter summarizes the perceived research gaps and solution approaches, and clarifies future research priorities in support of the overall direction of Smart Fire Fighting.

14.2 Overview of Research Roadmap Key Elements

The research priorities of this roadmap are based on key elements that have been distilled from a variety of sources collected throughout the overall effort. The recommendations to address perceived research gaps and solution approaches have been separated based on common features into four primary categories: Standardization; Developmental Gaps; Broad Conceptual Gaps; and Solution Approaches. The genesis of these four key elements are rooted in the core chapters (Chapters 2 through 12) of this roadmap. An overview of these key elements and associated research gaps and solution approaches is illustrated in Figure 14.1.

14.3 Standardization

Among the key elements for advancing CPS-Smart Fire Fighting, the importance of standards and similar guiding documents used by the applicable communities are paramount. Standardization establishes the baseline mindset, and without them, meaningful forward progress is handicapped.

The perceived research gaps collected from the core chapter priorities are illustrated in Figure 14.2, and the following summarizes the identified subitems for Standardization, with a focus on data-related standards:

- Current infrastructure assessment (Chapter 2, Data Gathering)
- Implementation of sensor technology (Chapter 3, Data Gathering)
- Standardization (Chapter 4, Data Gathering)

Figure 14.1 Research priorities for CPS-Smart Fire Fighting.

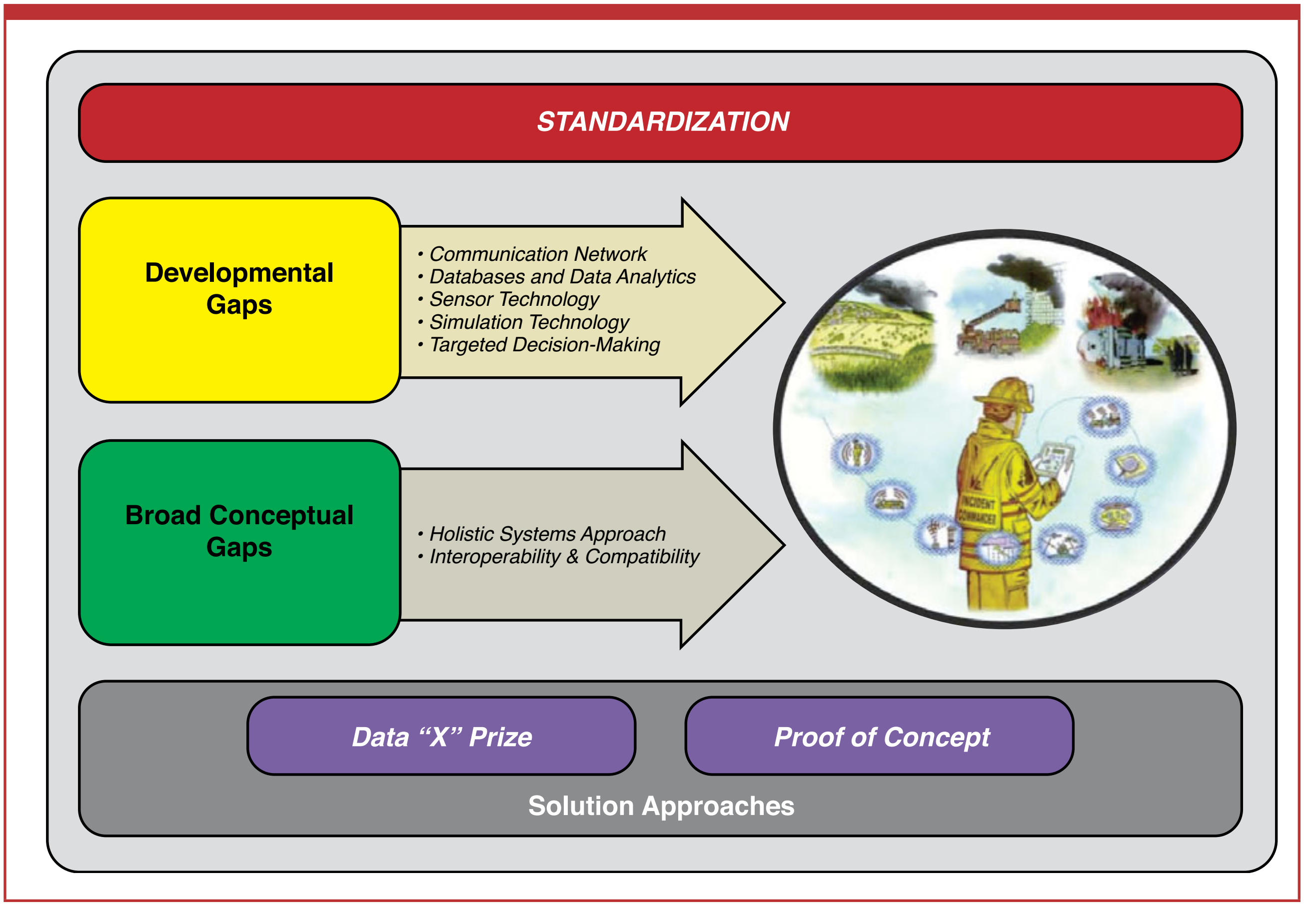
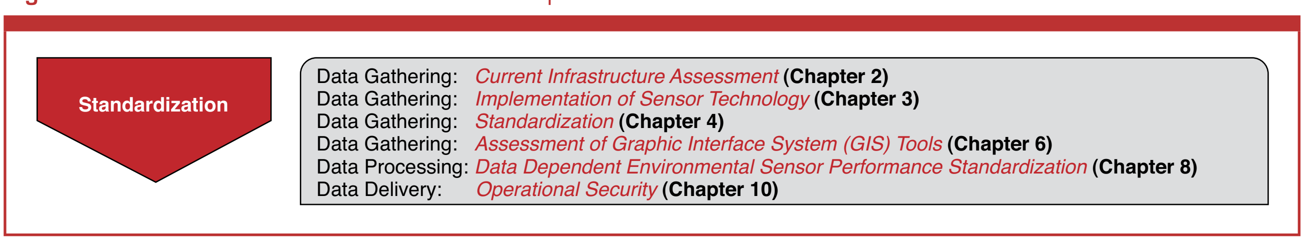


Figure 14.2 Standardization issues in core chapters.



- Assessment of graphic interface system (GIS) tools (Chapter 6, Data Gathering)
- Data-dependent environmental sensor performance standardization (Chapter 8, Data Processing)
- Operational security (Chapter 10, Data Delivery)

Standards that are applicable to Smart Fire Fighting are documents that address detailed technical issues and are typically developed in private consensus-writing processes using volunteer subject-matter experts. In a general sense, they represent the will of the standards body on complex technical topics. Ultimately, they are a critically important means for instituting broad policies (e.g., promoting interoperability), enabling important marketplace conformity in support of end-user needs (e.g., establishing interoperable communications protocols), and documenting critical baseline technical information that can be more readily proliferated (e.g., addressing data exchange of the fire service).

The primary focus of standardization is generally to address technical issues, but other issues that are arguably more political, societal, cultural, legal, and so on, also need to be addressed. For example, handling data often involves proprietary and private information, such as medical records for a person involved in a medical event requiring an ambulance. Who should have access to which data and information, and what are the ethical responsibilities?

Another vivid example revolves around the strong interest for the use of unmanned aerial vehicles (UAVs) by the emergency response community. This technology has already outpaced the infrastructure needed to support it, since commercial and private (i.e., hobby-oriented) UAVs are available and can readily serve emergency responder needs. But standards are needed for training and safe operation, and questions abound on a multitude of nontechnical details [1]. For example, should licenses be required? Who should be allowed to operate UAVs? How can legitimate privacy concerns of the public be addressed? How will liability be handled, if a device crashes into a person or interferes with commercial aviation?

A robust standards infrastructure already provides a solid standardization foundation for the emergency response community. The proliferation of Smart Fire Fighting requires this to be expanded and seamlessly adapted with the world of cyber-physical systems. Specific standards are needed for detailed topic areas such as sensors on-board individual fire fighters, as well as broad systematic standards to address overarching technical issues such as the development of a sweeping communications protocols such as the FirstNet initiative [2]. Some of these standards exist, but more will be needed, and their development will be key to the successful deployment of Smart Fire Fighting.

Standards need to address all aspects of a fire fighters' job, not only on the fireground but also pre-event (e.g., fire inspections, education) and post-event (e.g., investigations, training). Standards are the essential elements of the supporting infrastructure and are needed to address key topic areas such as planning, preparedness, response, and recovery.

- Planning: capability assessment, vulnerability assessment, risk assessment, inspections
- Preparedness: pre-incident planning, resource deployment, training and exercises
- Responses: computer-aided dispatch, in-vehicle routing, mobile field intelligence, search and rescue coordination, mass evacuation, mass sheltering, public notification, and multi-disciplinary coordination
- Recovery: damage assessment, debris removal, infrastructure restoration, community recovery, environmental stabilization, and public information

14.4 Developmental Gaps

This section addresses the key elements that relate to research gaps for specific developmental issues. For convenience, these are illustrated in Figure 14.3.

Further review of all the developmental gaps considered throughout this roadmap fall into the following five focus subareas for research: Communications Network; Databases and Data Analytics; Sensor Technology; Simulation Technology; and Targeted Decision Making. These subtopics are populated with the specific research priorities identified in Chapters 2 through 12.

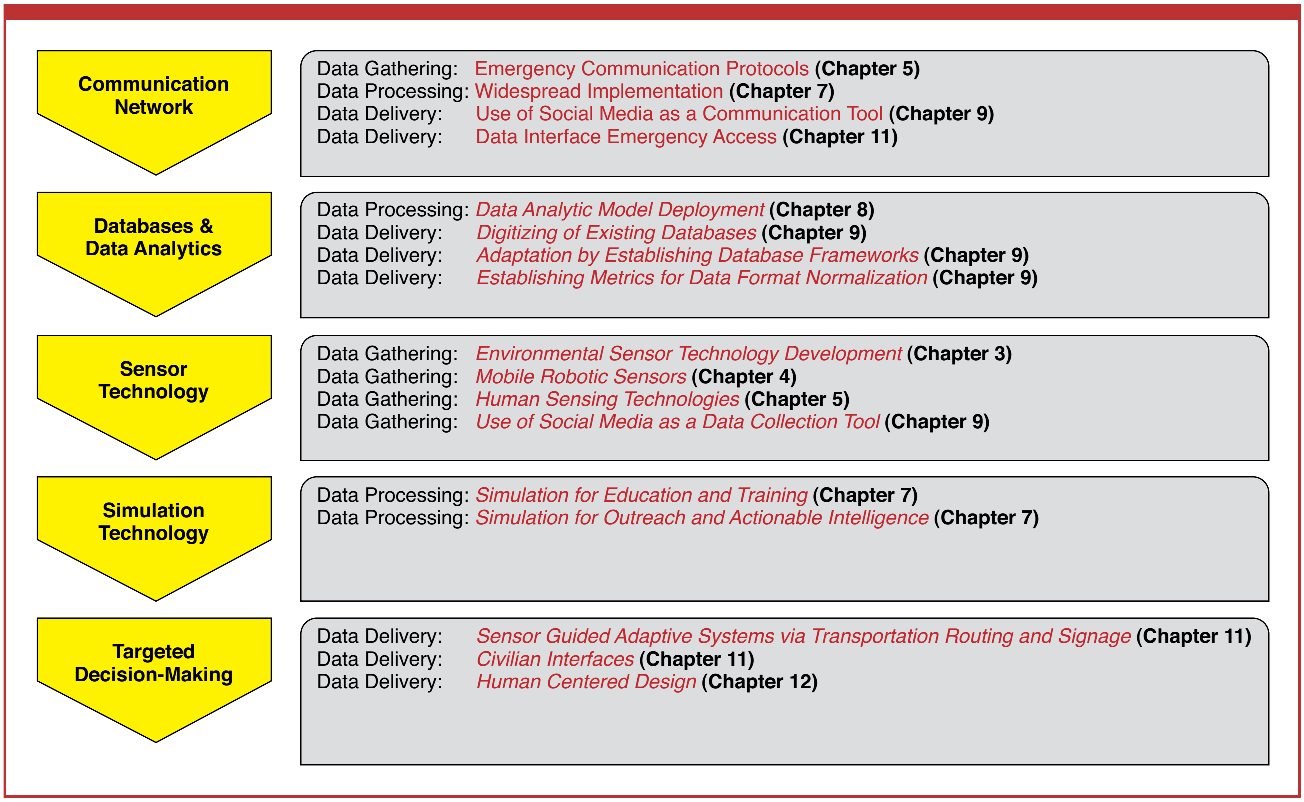
14.4.1 Communications Network

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Communications Network:

- Emergency communications protocols (Chapter 5, Data Gathering)
- Widespread implementation (Chapter 7, Data Processing)
- Use of social media as a communication tool (Chapter 9, Data Delivery)
- Data interface emergency access (Chapter 11, Data Delivery)

Without a practical and functional communications network, all the data and information involved with Smart Fire Fighting will not be available or complete. Communications represents the pipeline that will ultimately allow and support data transfer, and it is a critical part of the overall supporting infrastructure.

Figure 14.3 Developmental gaps in core chapters.



A robust, reliable, trustworthy communications network will require communications protocols that will seamlessly facilitate operations through multiple cascading operating platforms (i.e., on-board personnel, between personnel, between fireground units, between incident commanders, multi-jurisdictional). The information collected from all sensors will be of little value unless it can be efficiently conveyed to the platforms, where it is processed, and in turn conveyed to the end user through targeted decision-making platforms.

Regional data platforms and regional communications infrastructures are areas with significant potential to leverage Smart Fire Fighting. An example is computer-aided dispatch (CAD); it already exists in data platforms and communications protocols. CAD-to-CAD regional communications and multidiscipline communications (i.e., the fire service; law enforcement; transportation, health, and building departments; public and private schools and universities; public works) offer a prime method to vastly improve the backbone of the emergency response infrastructure. These systems are functional today and are capturing and processing vast amounts of data; coordinating this activity would have far-reaching impact.

Today's wireless communications world is relatively complex and already well established. Thus, the optimum business approaches will need to be considered for supporting the proliferation of technology and widespread implementation of communications concepts supporting Smart Fire Fighting. Further, new technology or systems are also emerging in this field, which sometimes allow unique and unexpected advantages. For example, after the Haiti earthquake in January 2010, the primary communications infrastructure failed and the primary mode of communication available to reach inhabitants on the front lines was through social media. As another example, digital volunteers are a new emerging contributor of emergency services, who, like ham radio operators of previous decades, are social media–savvy spectators recruited to help identify and filter emergency calls [3].

One concept of focused interest is the establishment of secondary communication interfaces that will have limited access for use by only emergency responders to perform their assigned duties. This concept recognizes that some information may be private or proprietary and will require special handling. This would be similar to the "locked-box" type approach currently used today by many fire departments to provide a building key in a locked box (accessible only by the fire service) at the entrance of all commercial establishments so that emergency responders can gain entry during an emergency. The communications interfaces will require standardized designs and protocols to allow access only by those with approved clearance.

14.4.2 Databases and Data Analytics

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Databases and Data Analytics:

- Data analytics model deployment (Chapter 8, Data Processing)
- Digitizing of existing databases (Chapter 9, Data Delivery)
- Adaptation by establishing database frameworks (Chapter 9, Data Delivery)
- Establishing metrics for data format normalization (Chapter 9, Data Delivery)

The value of databases and data analytics is evident by the multiple programs emerging throughout the landscape, such as the San Francisco 3-1-1 Initiative [4], the Tennessee Fire Department Research Center [5], and the FDNY Analytics Unit [6]. We are living in a sensor-rich world with vast amounts of data that are already available, and we are adding to this data at amazing rates. Going forward, various components of the data infrastructure need to be developed and universally standardized. For example, terminology requires agreement, and metrics are needed to normalize data according to spatial and temporal setting for which the data can be used (e.g., the need for time measurement protocols for sensors, a.k.a., device clocks).

Current data collection methods used by the modern fire service are still largely based on hard-copy forms for both pre and post-events. In this regard, consider existing national data collection systems such as NFIRS, NEMSIS, N-FORS, and BATS. These approaches need to be adapted to the latest electronic methods and existing data digitized wherever possible. The widespread use of electronic data entry needs to be facilitated. Where the data collection methods are lacking or nonexistent, data collection frameworks need to be established so that uniform data are collected going forward. Coordination of incoming data at all levels is essential. An example is the collection and processing of CAD data used independently by all fire departments, which if properly coordinated, could be used to collect national data statistics. Ultimately, a vision is for such national data to be available in real time to the end-user community.

A concept mentioned earlier and worth repeating is the systematic handling of data utilizing the “cloud” as the centralized focus for data storage. The advantages are believed to outweigh the disadvantages, which recognizes the long-term value of a unified, secure, reliable data-storage platform used by emergency responders. The use of the cloud would allow the seamless integration of infrastructure and analytics in a dynamic manner based on what is available. A centralized cloud source of data could support real-time data analytics of important statistical information that today is the backbone of many important programs.

14.4.3 Sensor Technology

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Sensor Technology:

- Environmental sensor technology development (Chapter 3, Data Gathering)
- Mobile robotic sensors (Chapter 4, Data Gathering)
- Human sensing technologies (Chapter 5, Data Gathering)
- Use of social media as a data collection tool (Chapter 9, Data Gathering)

Sensor technology development is already a robust field, with the fire service benefiting from the ongoing evolution of better technology in other fields such as the military and industrial confined space entry in shipyards. However, there is much room for improvements, and the environments faced by fire fighters are dramatically diverse, unpredictable, and dangerous. Because of the complexities of unknowns, arguably every structural building fire qualifies as both a confined space entry event and a hazardous materials event.

The need for sensors on the fireground is an area deserving focused research attention. The hostile environments faced by fire fighters is one that begs for robotics and remote sensing equipment. While much work has been done, more is needed. An example of extensive efforts includes the DARPA robotics challenge held annually as a competition of robot systems and software teams vying to develop robots capable of assisting humans in responding to natural and man-made disasters [7]. Another example is the extensive robotics work that has been addressed by a portfolio of ASTM standards intended to assist end users with evaluating, purchasing, and training with response robots [8].

This need for additional sensory input extends well beyond the conventional modes of measuring a hostile environment such as a building on fire. All incoming data is of value to fire fighters. We need means of capturing real-time information on the location of building occupants requiring rescue, especially those with physical disabilities. Real-time processing of critical building information is essential, such as building systems like elevators, ventilation systems, water supplies, and electric power. For fire fighters themselves, environmental sensors, biometric sensors, and sensors for geophysical tracking and location are all of high value, though far from maturity from a technological perspective.

Future sensor development will be expected to address a multitude of issues, some conventional and some not so conventional. Examples include the following:

- Use of telematics, remote sensing, unmanned vehicles, and integrating sensing and remote communications
- Additional sensors and improved hardening and reliability of the technology platforms
- Humanoid robotics and expansion of autonomous fire fighting search-and-rescue apparatus
- Autonomous swarming aerial robotics
- Development of forensic timelines based on stationary sensors that provide information throughout an incident
- Synchronization with occupant-carried sensors
- Utilization of social media as a tool, including as a source of data that can be mined and utilized

14.4.4 Simulation Technology

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Simulation Technology:

- Simulation for education and training (Chapter 7, Data Processing)
- Simulation for outreach and actionable intelligence (Chapter 7, Data Processing)

Fire fighting is dangerous, and simulation technologies offer strong promise to minimize or eliminate the injuries and fatalities that result from live training exercises. This is a maturing field that can exploit sophisticated models of fire physics, the gaming industry, and other applications parallel to fire fighting (e.g., the military) that needs to be adapted for fire service applications.

The proliferation of simulation offers strong advantages for realistic training and education, both for fire fighters and the public. Public education on the dangers of specific fire hazards, such as dry Christmas trees or the improper use of gasoline indoors, could be safely and more effectively demonstrated for public education campaign purposes.

Using simulation in a realistic virtual world as a mass-scale information provider opens up the area of the so-called actionable intelligence. Following the knowledge that can be retrieved from the computational space, system designers and others are given the tools to actually act and improve field operations whenever such an improvement is required and desired. Enabling widespread implementation requires understanding and supporting marketplace policies for the Smart Fire Fighting arena. Such implementation will need to coordinate with existing marketplace activity, which in some cases is already well established.

14.4.5 Targeted Decision Making

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Targeted Decision Making:

- Sensor Guided Adaptive Systems via Transportation Routing and Signage (Chapter 11, Data Delivery)
- Civilian Interfaces (Chapter 11, Data Delivery)
- Human Centered Design (Chapter 12, User Interface Delivery Methods)

The value-added efforts to gather data and to process data will be lost if the results cannot be delivered effectively to the end users. A critical part of cyber-physical systems is targeted decision making, which involves providing the needed information to end users when they need it in the manner they need it. Effectively delivering the information derived from data is paramount, and failure to provide the information in a meaningful manner can derail the entire "smart" effort.

To ensure successful integration of cyber-physical systems with fire fighting, human-centered design needs to be an inherent part of all systems, subsystems, and system components. This is an essential part of technology development, and ultimate usability will be determined based on the extent a component or product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use.

From a data delivery perspective, the context for targeted decision making generally revolves around administrative duties (e.g., office or station), responding to and from events, and the fireground or emergency scene. In this context, a multitude of interface and interaction paradigms are prime areas of interest for targeted decision making, including but is not limited to voice/speech technology, gesture, eye gaze, immersive/augmented reality, touch/haptics, wearable computer/electronic textiles/biosensors, vibrations, heads-up displays, context aware/location (situational awareness), and mobile devices.

Future research efforts are needed for the aforementioned topic areas, and they need to remain attentive to challenges such as technology transfer and user acceptance. Research is needed to overcome barriers to adoption and use, such as competition for end users' attention, cognitive overload, alert fatigue, system versus component view, interoperability and integration, user-centered design, and the need for new standards. From a computational standpoint, cognitive modeling would be a useful and meaningful long-term goal.

Targeted decision making is, however, more than simply dealing with a single person or end users one by one. It is not only fire fighters who are information recipients, but all the people affected by the emergency event, including building occupants and other members of the public. Often information is needed by several individuals or large numbers of targeted groups of people at the same time or at specified targeted time frames. Interfaces with civilians need to be easy to use, be personalized, provide critical information, and remain navigable in stressful situations.

Fireground information delivery includes, perhaps most obviously, the incident commander (IC), but the information the IC needs is different from what is required for other fireground personnel. For specific fire fighters or crews of fire fighters, the information may be task or assignment oriented to support activities such as primary search, roof-top ventilation, or hose line operations. Additional broad-scale and complex fireground examples are high-rise building fire alarm systems and mass notification used for evacuation of entire neighborhoods during a wildland-urban interface fire, each of which uses pre-programmed succinct automated messages based on scientifically established messaging profiles. These are part of the Smart Fire Fighting spectrum and are among the tools used by fire fighters to provide necessary actions to achieve their end goals.

To be effective and remain relevant, delivery interfaces need to be dynamic and adaptable to changing situations. For example, a common tactic for the evacuation of a building is through messages provided to occupants, with different messages used depending on the situation. Thus, adaptability is a critical characteristic of targeted decision making.

A case study example of a specific subarea of targeted decision making that has promise is the technology supporting speech-to-text transcription, speech activity detection, translation, and speaker identification. Fireground radio traffic is a strong candidate for this technology, and despite the variability of verbal activity, there is defined structure based on the National Incident Management System (NIMS) and NFPA 1561, Standard on Emergency Services Incident Management System and Command Safety [9].

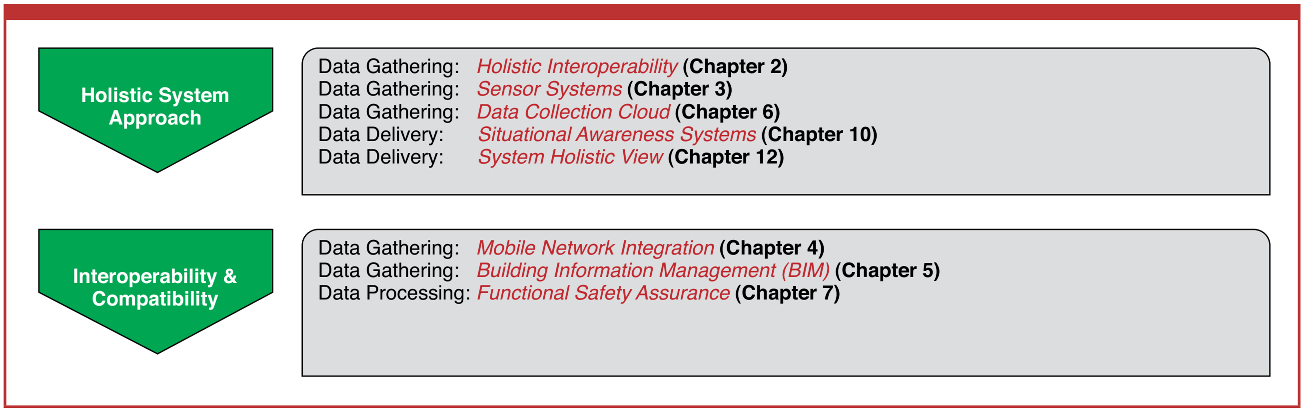
Certain spoken words could automatically trigger specific actions, such as indicating who has command or which units on scene are performing certain tasks. More important, the spoken word "mayday" signifies a fire fighter in trouble and immediately initiates multiple actions (e.g., deployment of the rapid intervention team), some of which could be automated. Further, the transcription of all event traffic would not only provide documentation for investigations and training purposes but also serve as an additional data compilation available for future mining.

14.5 Broad Conceptual Gaps

This section addresses the key elements that relate to research gaps for broad conceptual issues. For convenience, these are illustrated in Figure 14.4.

Further review of all the broad conceptual gaps considered throughout this roadmap fall into the following two focus subareas for research: Holistic Systems Approach, and Interoperability & Compatibility. These subareas are populated with the specific research priorities identified in Chapters 2 through 12.

Figure 14.4 Broad conceptual gaps in core chapters.



14.5.1 Holistic Systems Approach

The following perceived research gaps are taken from the core chapter priorities that have been identified as items for Holistic Systems Approach:

- Holistic interoperability (Chapter 2, Data Gathering)
- Sensor systems (Chapter 3, Data Gathering)
- Data collection cloud (Chapter 6, Data Gathering)
- Situational awareness systems (Chapter 10, Data Delivery)
- System holistic view (Chapter 12, User Interface Delivery Methods)

All components, subsystems, and systems should be addressed using a holistic systems approach. This is necessary to properly address all performance features, including their compatibility, interoperability, and integration with each other and with the overall system and the users. Going forward, data is needed that is unified and scalable in a system of systems.

A systems approach is necessary to integrate the sweeping array of sensory inputs that are available or are becoming available. Sensors must be viewed on a system level to adequately address features such as data logging, communications, and operational protocols. Improvements are required in a systematic way to assure dependability, stability, and rapid setup in support of an effective information-capture and communications infrastructure. Ultimately, a holistic systems approach would support seamless sensor integration in a totally integrated task-processing environment for use by realistic delivery interfaces.

A concept that inherently supports the systematic handling of data is better utilization of the "cloud" as the centralized focus for data storage. The advantages are noteworthy and would enable a unified platform with universal access by emergency responders. However, it also has technical and policy challenges based on the same attributes, that is, secure and reliable universal access by (only) emergency responders.

As an example, research efforts in cloud specific elements of the data collection on issues of response should be considered. The cloud would be researched and developed in such a manner that it would drive forward topics that support a particular effort such as residential fire safety and the use of smoke detectors. The use of the cloud would allow seamless integration of infrastructure and analytics in a dynamic manner. A centralized cloud source of data could support real-time data analytics of important statistical information, which is the backbone of many important programs.

14.5.2 Interoperability and Compatibility

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Interoperability & Compatibility:

- Mobile network integration (Chapter 4, Data Gathering)
- Building information modeling (BIM) (Chapter 5, Data Gathering)
- Functional safety assurance (Chapter 7, Data Processing)

Interoperability & compatibility are required between multiple communications protocols, to enable seamless operations through multiple cascading operating platforms (on-board personnel, between personnel, between fireground units, between incident commanders, multi-jurisdictional, etc.). Sensor technologies will need to be interoperable whether they are on-board personnel, brought to the scene via other equipment, or built in with the operating environment such as with building information modeling systems. All data processed will need delivery to the end user such that any method of targeted decision making will allow critical information to reach the end user with consideration of how they need it, when they need it, and in a manner that ergonomically maximizes the value of the data. In summary, the ideal technology integration for any particular component is available to the end user as "plug and play."

The need for interoperability & compatibility, for all components and subsystems, is a recurring theme throughout this research roadmap for Smart Fire Fighting. Interoperability is considered to be the ability to function on a common platform with similar equipment, and compatibility is the ability to co-exist with similar equipment (i.e., other equipment in the environment) [10].

As a minimum, various components in a system need to at least be compatible (i.e., they do not interfere or "step on" each other), but preferably are interoperable. Compatibility includes the ability to co-exist and function in the presence of external sources of interference (i.e., not controlled by the emergency responders). For example, PASS and other fire fighter body-worn wireless systems must function properly in the vicinity of a civilian WiFi or microcell installation, or more powerful broadcast transmitter, or even electrical noise from switching power supplies or motors. As a specific example, a recent event in Norwood, New York, involved unrelated local WiFi routers interfering with fire fighter SCBA wireless systems [11]. It is more challenging for engineers to design a system that is resistant to interference and can co-exist in a real environment with unrelated RF sources and/or electrical noise than it is to design a system that is compatible with itself or other similar devices that coordinate via an agreed-on protocol.

It is noted that interoperability & compatibility are part of a spectrum of important performance attributes for any particular system component and generally include performance attributes such as the following:

- Availability: the ability to be obtained
- Durability: the ability to last
- Maintainability: the ability to be serviced
- Operability: the ability to function
- Reliability: the ability to perform as expected
- Stability: the ability to not introduce problems
- Compatibility: the ability to co-exist with similar equipment (i.e., other equipment in the environment)
- Interoperability: the ability to function on a common platform with similar equipment

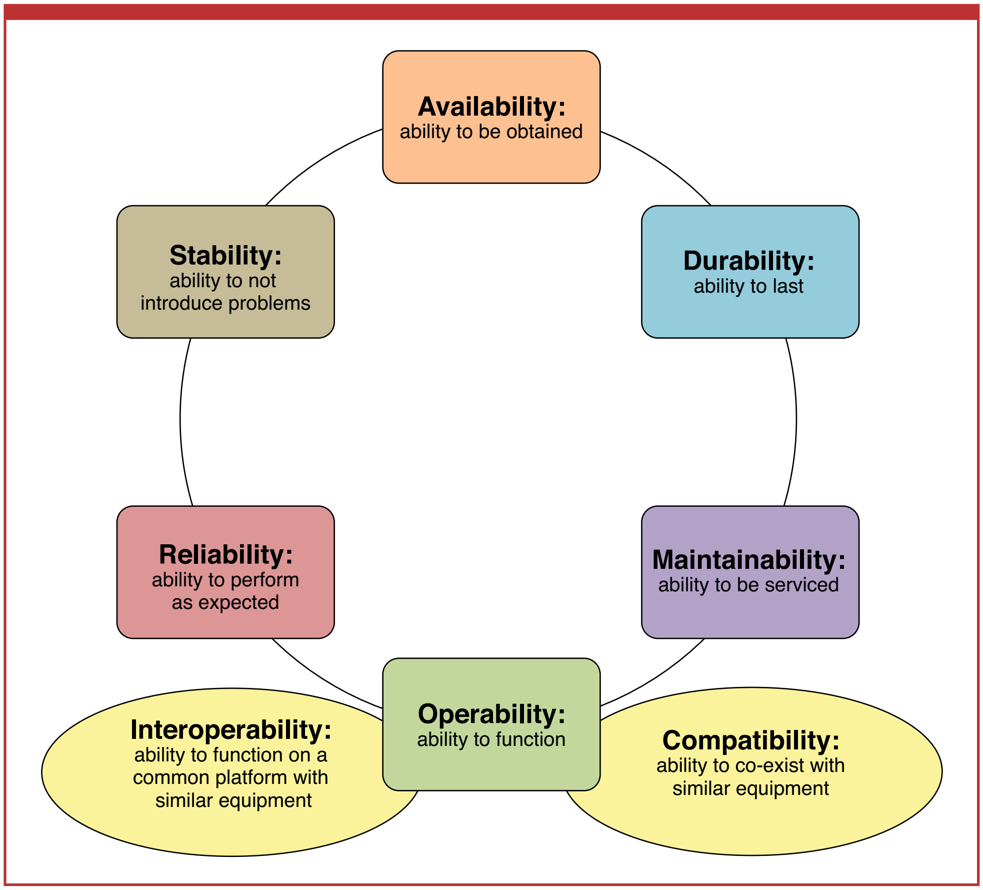
The key performance attributes and their relationship with interoperability and compatibility are illustrated in Figure 14.5. It is noted that the failure of any one of the attributes can ultimately doom the short- or long-term success of any particular component, subsystem, or system [10]. Other technical details have similarly been identified, such as the current requirements for fire fighting electronic safety equipment (ESE) have different standardized intrinsic safety design requirements for use in flammable or explosive atmospheres — this is an inherent handicap in the proliferation of a centralized interoperable ESE platform for fire fighters [10].

One vivid example is the need for development and implementation of a single effective operable platform for ESE used by fire fighters. Currently fire fighters carry multiple separate pieces of electronic equipment such as portable radios, flashlights, personal alert safety systems (PASS), thermal imaging cameras, electronics for the self-contained breathing apparatus (SCBA), in addition to the latest emerging hardware components such as GPS locator devices, physiological monitoring vests, augmented reality displays, and other technologies mentioned throughout this study.

Today, this equipment generally operates independently with separate power supplies and their own electronic and data protocols. The fire fighter end users are clear that weight and other factors are a problem and that this equipment should be more efficiently bundled [12]. Further, there have been compatibility issues with some equipment interfering with other equipment on the fireground, such as the audible tone from a PASS device interfering with the Vo-Coder of land mobile radios. A vision among fire service personnel is to have a single reliable electronics platform, similar to what astronauts use in the vacuum of space.

Smooth functionality requires that, for any given system, all involved subsystems and components are fully interoperable, consistent with the final intended function. Complete scalability is required to confirm proper function of all hardware and

Figure 14.5 Component performance attributes.



software. Several issues may potentially limit the scale of interoperability of hardware and software. Such issues include the need to universally identify subsystems and components in any given system and the need to reconcile the overall performance of the entire system with the performance of any particular subsystem and component.

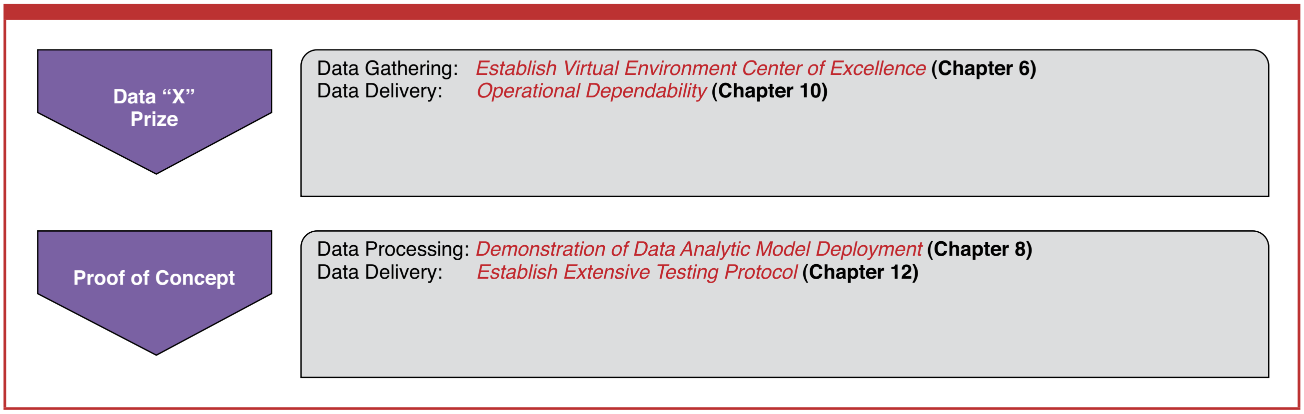
Specifically, the process by which systems are tested and certified to specific standards sometimes applies to a complete system and sometimes only to individual components of the complete system. The problem that evolves with either of these approaches, is that, absent a holistic perspective further division of the scale is significantly challenged, resulting in lack of interoperability. For example, if a subsystem, component, or accessory in a certified system is replaced, then, generally speaking, the system itself would no longer be certified to the particular standard. This has potential legal and policy implications that will inhibit the evolution of interoperability and compatibility.

14.6 Solution Approaches

This section addresses the key elements that relate to solution approaches for addressing research gaps. For convenience, these are illustrated in Figure 14.6.

Further review of the solution approaches considered throughout this roadmap fall into the following two focus subareas: Data "X" Prize, and Proof of Concept. These subareas are populated with the specific research priorities identified in Chapters 2 through 12.

Figure 14.6 Solution approaches in core chapters.



14.6.1 Data "X" Prize

The concept of a Data "X" Prize is intended to symbolize all research approaches that use a competitive challenge to establish meaningful problem resolution. This approach can be particularly effective for topic areas like CPS-Smart Fire Fighting that have numerous emerging organizations (e.g., high-tech start-up companies) that need to be coordinated towards a common goal. The following perceived research gaps are collected from the core chapter priorities that have been identified as subitems for Data "X" Prize:

- Virtual environment for a center of excellence (Chapter 6, Data Gathering)
- Operational dependability (Chapter 10, Data Delivery)

The concept of a Data "X" Prize has significant merit in this arena as an effective and efficient method for motivating the community at large toward clearly identified end goals. Currently, the entire emergency responder support infrastructure (equipment, training, standards, etc.) is significant, and all of it needs to be considered in the drive to implement new approaches involving Smart Fire Fighting. The Data "X" Prize concept provides a means for leveraging the talents and resources of all interested constituents, including end users, manufacturers, regulators, insurers, researchers, and so on.

One arena that serves as a model for this approach and that is related to Smart Fire Fighting is the ongoing robotics efforts being coordinated by the National Institute of Standards and Technology (NIST). In a multi-year program, NIST has clearly demonstrated the effectiveness of competitions to support the development and dissemination of standardized test methods that can be used by purchasers and others to evaluate performance characteristics of this emerging technology [13].

This competition-based setting allows for ongoing iterative refinement of test methods in response to new developments and has cultivated vibrant technology development in support of emergency responders and others. At this time, more than 60 robot test methods have been or are under development in the ASTM standards arena, exemplifying the merits of a competition-oriented approach [14]. Based on the success of this prize-type approach, the program is now shifting toward building the supporting infrastructure for the development of other aspects of the infrastructure in support of robotics, such as end-user training and certification of products and operators.

For a Data "X" Prize approach to be successful, it needs to clearly outline its objectives and focus on specific subareas breed strong competition among participants based on anticipated results that are achievable. Multiple focus areas are potential candidates, including the following examples:

- Implementation of a single operable electronic safety equipment (ESE) operational platform
- Development of a fully resilient and dynamic communications network
- Demonstration of novel user interface delivery methods
- Establishment of a easily and fully accessible data center for national statistics

- Creation of a realistic simulation for live fire training
- Creation of a realistic simulation for forensics

An additional concept related to a Data "X" Prize approach is the development of centers of excellence (e.g., Fusion Centers) to support a virtual testing environment. Such a center could be an administrative host for the Data "X" Prize approach in a multitude of technical topic areas. This would support cohesive advancement across the primary elements of planning, response, preparedness, and recovery and coordinate associated communities to allow cross-fertilization and best practices to proliferate.

14.6.2 Proof of Concept

The following are the perceived research gaps collected from the core chapter priorities that have been identified as subitems for Proof of Concept:

- Demonstration of data analytic model deployment (Chapter 8, Data Processing)
- Extensive testing protocol (Chapter 12, User Interface Delivery Methods)

Similar to the Data "X" Prize concept, the proof-of-concept approach provides a general research methodology that has merit for research to develop Smart Fire Fighting. This can be particularly effective in areas, like fire fighting, where there are already established marketplaces and an abundance of emerging technologies with significant potential impact. This approach provides a means to organize and evaluate the most promising technologies of the greater community.

For example, multiple promising technologies exist or are currently being developed that can directly address situational awareness in the wildland-urban interface (WUI). Specific examples are multiple global positioning system (GPS) and geographic information system (GIS) mapping hardware and software. The value of this technology is important and could greatly assist the fire-fighting end user, such as potentially providing crucial real-time information during events like the Yarnell Hill (Arizona) fire event in 2013, which resulted in 19 fire fighter fatalities [15]. A proof-of-concept approach will not necessarily create any new technology but instead will sort through the landscape of available solutions.

This approach would support Smart Fire Fighting at all levels, such as development of sensors, communications systems, data analytic models, and human cognitive delivery methods. In the case of Smart Fire Fighting, where technology developments are proceeding at an incredible pace and often ahead of the supporting infrastructure, research projects focused on proof of concept could be especially valuable. The ultimate value of Smart Fire Fighting is contingent on robust involvement of the end users and a full understanding of their needs, which are inherent with proof of concept–type approaches.

14.7 Overall Summary and Next Steps

The word *Smart* is appearing everywhere these days. Instances include Smart Machines, Smart Grid, Smart Manufacturing, Smart Cities, and Smart America, just to name a few. This trend is expected to increase. In a recent Harvard Business Review article [16], the authors discuss the impending emergence of a wide range of Smart products and systems and the likely impact this will have on both business and society. Although some smart systems are already implemented, huge challenges remain in terms of engineering these products and systems to attain their full potential. A key area, ripe for development, is Smart Fire Fighting.

The purpose of this research roadmap is to provide an overview of the current state and future trends of Smart Fire Fighting. Today's fire fighting and fire protection environment is data poor and without integrated analysis and decision making. Changing this situation will require new types of technologies.

The vision of Smart Fire Fighting can be realized by harnessing the power of emerging information, communication, sensor, and simulation technologies to enable markedly better situational awareness, predictive models, and decision making. Many of the most exciting uses of those technologies are in the area of cyber-physical systems, which is the focus of this research roadmap.

The roadmap presents a series of research needs prioritized to advance Smart Fire Fighting. The priorities have been distilled from research recommendations collected through a number of mechanisms, including the Smart Fire Fighting Workshop [17], the coordinated efforts of each core chapter team, a review meeting of the roadmap (held November 4, 2014, in Crystal City, VA), feedback from multiple presentations on this topic during the course of the project, recent literature on this topic, and assorted additional input.

As a result of this information, the recommendations to address perceived priorities for Smart Fire Fighting have been separated based on their common features into four primary key element categories and associated subareas:

- Standardization
- Broad conceptual gaps
  - Communication network
  - Database & data analytics
  - Sensor technology
  - Simulation technology
  - Targeted decision making
- Developmental gaps
  - Holistic systems approach
  - Interoperability & compatibility
- Solution approaches
  - Data "X" prize
  - Proof of concept

For each of the identified research focus areas, there is significant detail with specific focus topics for research included in the core chapters of this report. There is a wide range of specific possible research projects that could and should be considered for any particular subarea. Figure 14.7 offers case study examples of research projects that have characteristics that merit consideration.

These specific research gaps and solution approaches need to be further addressed to support the vision of Smart Fire Fighting (see Chapter 1). With the issuance of this research roadmap, next steps should include further outreach events to evaluate and implement identified research priorities. This research roadmap should be considered a living document and subject to periodic update and re-issue.

The occurrence of an emergency is a realistic expectation in all corners of civilization. Virtually all data is important for fire fighters and others in the emergency response community, and in the eyes of CPS professionals this sets the emergency response community apart from all others.

Enabling progress on the range of challenges facing CPS will take experts from many technical disciplines. As other sectors are working on critical gaps in CPS standards and metrics, the development of Smart Fire Fighting will be accelerated through coordination and collaboration with others working on CPS. As networks get faster and more prevalent, as detectors become smaller and less expensive, and as computers become more powerful, the potential for impact on fire fighting and public safety using Smart Fire Fighting will continue to expand. The question is not whether Smart Fire Fighting will happen but, rather, what it will look like, how effective it will be, and when it will happen — it's just a matter of time.

Figure 14.7 Example case study projects for CPS-Smart Fire Fighting.

	Example Case Study Projects	Core Chapter
Standardization	Establish a reliable and secure cloud based data storage approach for fireground use.	Chapters 2, 3, 4, 6, 8, and 10
Communication Network	Establish unified communication protocols to support interoperable electronic fireground equipment.	Chapters 5, 7, 9, and 11
Databases & Data Analytics	Coordinate computer aided dispatch data in support of nation data statistics.	Chapters 8 and 9
Sensor Technology	Enable emerging technology and the Internet of things as sensor inputs to indicate environmental fire conditions.	Chapters 3, 4, 5, and 9
Simulation Technology	Develop realistic flashover trainers using advanced simulation technologies.	Chapters 7
Targeted Decision-Making	Establish optimized information delivery to incident commanders.	Chapters 11 and 12
Holistic System Approach	Establish a reliable and secure cloud based data storage approach for fireground use.	Chapters 2, 3, 6, 10, and 12
Interoperability & Compatibility	Develop a fire fighter ensembles of interoperable electronic safety equipment that utilizes the same power source and communication protocols.	Chapters 4, 5, and 7
Data "X" Prize	Advance emerging technology for sensor development, robotics, data processing, targeted decision making and other data related applications.	Chapters 6 and 10
Proof of Concept	Evaluate GIS and similar situational awareness tools in real WUI environment.	Chapters 8 and 12

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