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PREFACE

In the manufacturing sector vast increases in efficiency and productivity have been achieved in the past 20 years through automation. In order to reap similar benefits in the construction, repair, and retrofit industries, which account for nearly 13% of GDP in the United States, means must be established by which the status of a complex job-site may be assessed instantaneously through automated, advanced metrology systems; by which machinery can be operated in both partially and fully autonomous capacities; and in which data flows seamlessly from architectural inception through job site implementation. During the next 20 years these topics are expected to form one of the highest priority research areas in the civil engineering arena.

In the fall of 1994 a research initiative at NIST was developed in construction automation, in alignment with needs projected by the Subcommittee on Construction and Building, Civilian Industrial Technology Committee, of the National Science and Technology Council. This carried the highest levels of support from NIST management as one of six new areas of fundamental investigation for Fiscal Year 1996. In preparation for this work, then estimated to be funded at $6M/year, an industry-government workshop was held to solicit feed back from a representative selection of U.S. construction companies as to the efficacy and utility of the proposed research. Topics on the agenda included 1) sensors for Real-time metrology; 2) wide band telemetry and data acquisition; 3) virtual site simulation and object representation standards; 4) person-in-the-loop systems, including head-up displays and tele-operations; and 5) construction robotics.

The workshop was held at the NIST, Gaithersburg, Maryland campus on March 30 and 31st, 1995. The format consisted of a series of keynote lectures from NIST and industry on Thursday, March 30th, followed by a round robin discussion on Friday March 31st. For the Thursday lectures, questions are set in italic style while the speaker's response is in normal text. In each case, the names of the discussion participants are listed at the start of each exchange. A similar switching of text style is employed for the round robin discussions to more clearly delineate each speaker's comments.

Bill Stone
NIST, Gaithersburg
May 1996

ABSTRACT

A two-day workshop on Construction Automation was hosted at NIST during March 30-31, 1995. Research programs actively underway at NIST in this area include the development of sensing systems, hardware, and software algorithms for advanced real-time construction site metrology; wide band telemetry and data acquisition [the ability to track many sensors at once through wireless communications]; virtual site simulation and object representation standards [development of robust virtual reality models for construction site objects and machines]; person-in-loop systems [including head-up displays, virtual simulators, tele-operations workstations, and portable database interrogators]; and semi-autonomous machine operations. These topics, and the need for database and machine interfacing standards, were discussed by workshop participants representing industry, government, and academe. Specific invited presentations included laser distancing, non-line-of-sight and kinematic GPS metrology, automated data exchange standards, real-time kinematic modeling, military helmet-mounted displays, virtual reality displays, construction robotics, automated excavation, virtual site representation, and automated building construction.

KEYWORDS: automated building construction, automated excavation, construction automation, construction robotics, data exchange standards, helmet-mounted displays, laser metrology, non-line-of-sight metrology, telemetry, virtual reality displays, wireless communication.

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1.1 Workshop Introduction

Richard N. Wright
Director
Building and Fire Research Laboratory, NIST

Let me take this opportunity to welcome each of you to NIST and to Gaithersburg, Maryland. I would like to take this opportunity to present some information on recent developments concerning federal research and development funding, some of which pertains to work being discussed here today.

Construction and Building Subcommittee

Background:

The National Science and Technology Council (NSTC), a cabinet-level group charged with setting federal technology policy, coordinates R&D strategies across a broad cross-section of public and private interests. NSTC has established nine research and development committees, including the Committee on Civilian Industrial Technology (CCIT), to collaborate with the private sector in developing a comprehensive national technology policy. The purpose of CCIT is to enhance the international competitiveness of U.S. industry through federal technology policies and programs. The Subcommittee on Construction and Building (C&B) of CCIT coordinates and defines priorities for Federal research, development, and deployment related to the industries that produce, operate, and maintain constructed facilities, including buildings and infra-structure.

Mission of the Subcommittee on Construction and Building (C&B):

The mission of C&B is to enhance the competitiveness of U.S. industry, public and worker safety and environmental quality through research and development, in cooperation with U.S.industry, labor, and academia, for improvement of the performance of constructed facilities. C&B addresses Administration goals to:

- Forge partnerships with industry to strengthen America's industrial competitiveness and create jobs.

- Make environmental protection, safety, and energy efficiency fully consistent with other business objectives.

The Construction Industry

Construction is one of the Nation's largest industries and a critical asset for enhancing the international competitiveness of U.S. industry. In 1994, new construction and renovation combined amounted to $850 billion, about 13% of the GDP, and provided employment for over 10 million persons. Constructed facilities shelter and support most human activities. Their quality is vital to the competitiveness of all U.S. industry, the safety and quality of life of the people, and environmental quality.

C&B Member Agencies:

Agencies (listed below) participating in the Subcommittee include agencies with responsibilities as owners and operators, regulators, and researchers.

Department of Agriculture (Forest Service)
Department of Commerce, Co-chair (National Institute of Standards and Technology)
Department of Defense (Corps of Engineers)
Department of Energy, Co-chair
Department of Health and Human Services (National Institute for Safety and Health)
Department of Housing and Urban Development
Department of Interior (U.S. Bureau of Mines) (U.S. Geological Survey)
Department of Labor (Occupational Safety and Health Administration)
Department of Transportation (Federal Highway Administration)
Department of Veterans Affairs
Consumer Products Safety Commission
Environmental Protection Agency
Federal Emergency Management Agency
General Services Administration
National Aeronautics and Space Administration
National Science Foundation

New Construction:

New construction put in place in 1994 represents about $508 Billion (which is about 60% of the total construction market). The breakdown between the five sectors of the industry; residential, commercial, industrial, institutional, and public works is as follows:

Commercial	10%
Residential	46%
Industrial	14%
Institutional	4%
Public Works	28%

Life Cycle of Constructed Facilities:

Construction includes the whole life of the project: initial planning and programming, design, procurement, construction, occupancy and maintenance, condition assessment, retrofit and renovation or removal. This whole life viewpoint is necessary to give realistic attention to values and costs of constructed facilities. For instance, for an office building, the annual operating cost, including salaries of occupants, roughly equals the initial construction cost. The primary value comes from the productivity of the occupants, which depends on the capability of the building to meet user needs throughout its useful life. Some technical innovations in facilities, such as those for durability, efficiency, or improved safety against natural disasters, may add to the initial cost but reduce the life cycle cost. Different sectors of the industry and their customers place different emphases on the importance of life cycle cost.

Industries of Construction:

Construction involves many industries including:

- Architectural and engineering design
- Finance
- Construction
- Insurance
- Construction equipment manufacture
- Facility management
- Materials manufacture
- Security
- Installed equipment manufacture
- Cleaning services
- Furnishings manufacture
- Fire protection
- Maintenance and repair
- Demolition

Vision:

The vision for the construction and building industries is:

Competitive

High quality constructed facilities support the competitiveness of U.S. industry and everyone's quality of life.

High Quality

U.S. industry leads in quality, speed and economy in the global market for construction products and services.

Efficient and Sustainable

The construction industry and constructed facilities are energy efficient, sustainable in use of resources, safe and healthful.

Hazard Resistant

Natural and manmade hazards do not result in disasters.

National Construction Goals

The C&B Subcommittee has studied research priorities expressed by the construction industry in industry forums and in proposals for the Advanced Technology Program of the Depart-ment of Commerce. Two priority thrusts; better constructed facilities, and health and safety of the construction workforce, were defined for focus of research, development and deployment (RD&D) in the construction and building area. The C&B program plans to make technologies and practices capable of achieving the goals under these thrusts available for general use in the construction industry by 2003. The baseline for measuring progress against the goals will be today's business practices. Therefore, reliable baselines and measurement tools need to be established and developed.

Long delivery time, waste and pollution, and construction work illness and injury contribute substantially to unnecessary increases in the cost of construction. Therefore, achievement of these goals will reduce construction cost and make housing more affordable through reduction in first cost and life cycle cost.

The C&B program and goals were reviewed with a focus group of industry leaders convened on April 5, 1994, by the Civil Engineering Research Foundation. These leaders strongly endorsed the goals.

Goals - Rationale:

Better Constructed Facilities

• 50% Reduction in Delivery Time

Reduction in the time from the decision to construct a new facility to its readiness for service is vital to industrial competitiveness and project cost reduction. During the initial programming, design, procurement, construction and commissioning process, the need of the client for the facility is not being met; needs evolve over time so a facility long in delivery may be uncompetitive when it is finished; and the investments in producing the facility cannot be recouped until the facility is operational. The need for reduction in time to project completion is often stronger in the case of renovations and repairs of existing facilities because of interruption of ongoing business. Owners, users, designers and constructors are among the groups calling for technologies and practices reducing delivery time.

• 50% Reduction in Operation, Maintenance and Energy Costs

Operation and maintenance costs over the life of the facility usually exceed its first cost and may do so on an annualized cost basis. To the extent that prices for energy, water, sewage, waste, communications, taxes, insurance, fire safety, plant services, etc., represent costs to society in terms of resource consumption, operation and maintenance costs also reflect the environmen-tal qualities of the constructed facility. Therefore, reductions in operation and maintenance and energy costs benefit the general public as well as the owners and users of the facility.

• 30% Increase in Productivity and Comfort

Industry and government studies have shown that the annual salary costs of the occupants of a commercial or institutional building are of the same order of magnitude as the capital cost of the building. Indeed, the purpose of the building is to shelter and support the activities of its occupants. Improvement of the productivity of the occupants (or for an industrial facility, improvement of the productivity of the process housed by the facility) is the most important performance characteristic for most constructed facilities.

• 50% Fewer Occupant Related Illness and Injuries

Buildings are intended to shelter and support human activities, yet the environment and performance of buildings can contribute to illnesses and injuries for building users. Examples are avoidable injuries caused by fire or natural hazards, slips and falls, legionnaires' disease from airborne bacteria, often associated with a workplace environment (sick building symptoms) and building damage or collapse from fire, earthquakes, or extreme winds. Sick building symptoms include irritation of eyes, nose and skin, headache, and fatigue. If improvements in the quality of the indoor environment reduce days of productive work lost to sick days and impaired productivity, annual nationwide savings could reach billions of dollars. Criminal violence in buildings is a safety issue which can be addressed in part by building design. Reductions in illnesses and injuries will in-crease users' productivity as well as reducing costs of medical care and litigation.

• 50% Less Waste and Pollution

Improvement of the performance of constructed facilities that shelter and support most human activities, provides major opportuni-ties to reduce waste and pollution at every step of the delivery process, from raw material extraction to final demolition and recycling of the shelter and its contents. Examples are reduced energy use and greenhouse gas emissions and reduced water consumption and waste water production. Waste and pollution also can be reduced in the construction process: construction wastes are estimated at 20-30% of the volume of landfills.

• 50% More Durability and Flexibility

Durability denotes the capability of the constructed facility to continue (given appropriate maintenance) its initial performance over the intended service life, and flexibility denotes the capability to adapt the constructed facility to changes in use or users' needs. High durability and flexibility contribute strongly to the life cycle quality of constructed facilities since they usually endure for many decades.

Health and Safety of Construction Workforce

• 50% Reduction in Construction Work Illnesses and Injuries

A factor affecting international competitiveness is the cost of injuries and diseases among construction workers. Although the construction workforce represents about 6 percent of the Nation's's workforce, it is estimated that the construction industry pays for about one-third of the Nation's's workers' compensation. Workers' compensation insurance premiums range from 7 to 100 percent of payroll in the construction industry. Construction workers die as a result of work-related trauma at a rate that is 2 and 1/2 times the annual rate for workers in all other industry sectors (13.6 deaths per 100,000 construction workers, as compared to 5.5 deaths per 100,000 workers in all other industry sectors). Construction workers also experience a higher incidence of nonfatal injuries than workers in other industries.

Strategy:

To help the construction and building industries meet the above goals, the member Federal Agencies of C&B will:

- Work with industry
- Provide baselines and measures of performance
- Focus Federal R&D programs on automation, high performance materials and systems, measurement, and sustainability
- Provide tools for a more efficient regulatory process
- Provide tools for acceptance of innovation

- Use Federal construction for technology demonstration

- Set goals and milestones for the program and measure effectiveness

Working with Industry

The Construction and Building Subcommittee's program and goals were reviewed with a focus group of industry leaders convened on April 5, 1994, by the Civil Engineering Research Foundation. The response of the focus group is described in the Construction Industry White paper "Innovation in the U.S. Construction Industry: An Essential Component for America's Economic Prosperity and Well Being." The white paper is an industry perspective of methods and means that, if jointly supported and implemented by the public and private sector, prom-ise to transform the construction sector into the high technology/high skill sector America requires. Construction industry leaders strongly endorsed the goals established by C&B. The industry leaders urged expanded dialogue and the immediate initiation of actions.

On December 14-16, 1994 industry leaders held a White House Construction Industry Workshop on National Construction Goals organized by the Civil Engineering Research Foundation . The workshop's purpose was to provide an industry perspective on the priorities among proposed construction goals and develop recommendations for an appropriate implementation plan. Participants in the workshop included representatives from design, construction, labor, construction equipment, building materials and mechanical equipment, finance, insurance, owners, codes, etc.

Industry Perspective:

The results of the White House Construction Industry Workshop are reported in a CERF report "National Construction Goals: A Construction Industry Perspective. The workshop noted that the five sectors of the construc-tion industry: residential, commercial, industrial, institutional, and public works differ in the participants involved, methods of financing, legal factors, project timing, the desire for or acceptance of innovation, the importance first cost or operating cost, market forces, and customer involvement. Consequently, they differ in their ranking of relative importance of the proposed goals. For example, residential construction specifically identified reduced first cost (directly coupled to reduced delivery time) as their most important goal. Goals that are considered of highest priority to the industry are identified in the chart (Figure 1.1.1) as double diamond, and those of lessor priority with a single diamond.

Meeting the goals will require advances in technology, demonstration of those advances, and leadership to bring about the important non-technical changes called for by industry. Lack of present knowledge makes less feasible the important goals for Productivity and Comfort, and Occupant Health and Safety. The workshop encouraged research in these important areas to make advances toward these goals possible in the near future.

Goal:	Residential	Commercial	Institutional	Indus-trial	Public Works	Rank
Delivery Time	♦♦	♦	♦♦	♦♦	♦	1
Operation Maintainence and Energy	♦	♦♦	♦	♦	♦♦	2
Productivity and Comfort		♦	♦			5
Occupant Health and Safety	♦					6
Waste and Pollution	♦				♦	5
Durability and Flexibility	♦♦	♦			♦	3
Worker Health and Safety	♦		♦	♦		4

Figure 1.1.1: Industry priorities for construction goals identified by C&B

Non-Technical Barriers:

At the April 1994 Focus Group the construction industry took note of the following major non-technical barriers to the introduction of technical innovations:

- Lack of Leadership
- Regulatory Barriers
- Liability
- Adversarial Relations, and
- Financial Disincentives

The following additional barriers were cited by industry at the December 1994 Workshop:

- Parochialism
- Increasing scarcity of skilled labor
- Fragmentation of the industry
- Inadequate owner involvement

Barriers are pervasive and more than anything else prevent or retard the application of badly needed innovation in the construction industry.

Barrier Removal:

Industry representatives identified a number of changes needed to remove barriers to private sector investments in technology required to meet the goals.

- a speed-up in the regulatory process, i.e., obtaining the necessary approvals,

- tort reform to avoid unreasonable liability from using innovations,

- performance standards and conformance assessment mechanisms to enable users and regulators to assess and accept new materials, products, and systems,

- education of builders, managers, regulators in information systems and data, and training of craft workers to increase the pool of skilled labor and to promote safe operating practices,

- a closer working relationship between all parties in the facility design and construction process, particularly in the early stages of planning and design, and

- formation of a construction coordination council that would guide private activities and speak for the industry to bring about some of the needed changes in the system.

Technology Advances:

Advances in seven areas of technology have been identified as contributing to a more competitive construction industry and helping to meet the goals for the industry.

1. *Information and Decision Technologies*

- Integrated data bases and information systems
- Knowledge systems as successors to standards and books
- Integrated project information systems
- Construction management technologies
- Collaborative decision making environments
- Post-occupancy evaluation systems

2. *Automation in Design, Construction and Operation*

- Simulation and visualization
- Computer-aided design
- Computer-integrated construction
- Advanced sensors
- Construction robotics
- Building automation systems
- Computer-aided facilities management
- All weather construction

3. *High Performance Materials, Components, and Systems*

- Advanced materials
- Advanced components
- Whole building systems
- Connections
- Mechanisms, models and data for life cycle perfor-mance
- Assessment and quality assurance technologies
- Renewal engineering
- Recycling and reuse
- Functional flexibility
- Improved water sealants
- UV barriers

4. *Environmental Quality*

- Energy conservation
- Indoor air quality
- Remediation of contaminated construction sites
- Sustainable development (ecological quality, conser-vation of non-renew able materials, etc.)

5. *Risk Reduction Technologies*

- Fire protection
- Toxic exposures
- Earthquake risk reduction
- Wind risk reduction
- Other hazards

6. *Performance Standards System*

- Performance standards for products and processes
- Test methods and data for life cycle performance
- Conformance assessment system
- Certification system
- Data bases availability and accessibility

7. *Human Factors*

- Cognitive processes and uses of information
- Physiology
- Ergonomics
- Environmental and person-machine interactions
- Team building and workforce efficiency

Plan for Deployment:

Barriers to the acceptance of new technology include the lack of knowledge of what is available, the benefits to be gained, the risks involved in initial uses of new technologies, and simply human resistance to change. A key part of this multi agency program is the showcasing of new technologies and methods for overcoming barriers. Federal construction and renovation projects provide an excellent showcase for these innovations, and enable all stakeholders to gain comfort with change.

Executive Order 12902, Energy Efficiency & Water Conservation at Federal Facilities, of March 8, 1994, requires that when an agency constructs at least five buildings in a year, it shall designate at least one building, at the earliest stage of development, to be a showcase highlighting advanced technologies and practices for energy efficiency, water conservation, or use of solar and other renewable energy. The order also requires that each agency designate one of its major existing buildings to become a showcase to highlight energy or water efficiency and attempt to incorporate solar and other renewable technologies, and indoor air quality improvements. Each agency is required to develop and implement plans and work in cooperation with the Department of Energy , and where appropriate, in consultation with the General Services Administration and other appropriate agencies to determine the most effective and cost effective strategies to implement these demonstrations. Efforts of the C&B can facilitate visibility for these projects and help underscore their significance to the housing and construction industries.

Federal Construction R&D Budget
($ Million)

The Administration has assigned priority for research and development to Construction and Building for the FY 1996 budget as "Activities that support the residential/commercial building construction industry and its suppliers in the development of advanced technologies aimed at increasing the productivity of construction, improving product quality (including energy efficiency and improved indoor air quality), use of renewable resources, and increased worker health and safety.

The following table reflects the changes proposed in the President's budget for construction R&D for fiscal year 1996 compared with the budget enacted for fiscal year 1995.

Agency	FY95 *	FY96 **
Dept. of Energy	59.5	63.9
National Science Foundation	55.0	57.3
Dept. of Commerce (NIST)	16.9	22.9
Dept. of Defense (Army Corps of Engineers)	0	15.8
Dept. of Agriculture	7.9	7.4
Dept. of Housing and Urban Development	2.0	2.0
TOTAL	141.3	169.3

* FY95 enacted budget
** FY96 President's budget request

Figure 1.1.2: Federal construction R&D

NOTE 1: In addition to the above budget figures, many agencies have C&B related research and development listed primarily for other NSTC activities, for instance, the National Institute of Occupational Health and Safety, Department of Health and Human Services, budgeted $14.3 million to construction worker and building occupant safety and health in FY 95 and FY 96.

NOTE 2: Other Federal agencies including the General Services Administration and the Department of Veterans' Affairs are involved in the deployment of new technology in construction but do not budget funds for construction research and development.

Closing:

Of course an important question is: what is the transition between a Presidential priority, a Presidential request, and actually having the funding here on October 1, 1995. I think the answer is that we can expect this Congress to be skeptical of all the President's requests. I think whether this succeeds or fails it depends entirely on whether our mission is being pursued effectively. We must provoke economic growth by working with industry to develop and apply new technology, measurements and standards. If the industry that we are serving -- the industry that we are working with -- feels this is important and chooses to let Congress know that, we have a good chance of getting the resources. I think our purpose with you over these two days is to be sure that the technical content of the program is one that merits support by industry and merits support by the federal government. Then we will have to look at the people whose concern is for technology policy to determine indeed whether Congress comes through with the funds this year.

I was asked earlier this morning for some information regarding MEP. The Manufacturing Extension Partnership is a nationwide network of technology transfer centers. These are not federal centers. These are organized by universities and industry associations, and they receive initially 50% of their funding from states or the private sector and the remaining 50% of their funding through NIST. There are constant negotiations with Congress on how long the government share of the funding will endure. There are regular reviews of the program. But the thought -- and the President's objective -- is to have 100 technology transfer centers nationwide so that every businessman is within an easy drive of the center. They were originally set up for the scenario where a small machine shop wants to purchase the automation equipment that will let it compete in its market but doesn't have all the knowledge needed to make this transition. The purpose of the MEP center is so that the owner can drive there, touch, feel, taste and pick up the portfolio of software and hardware that should be incorporated in his business and get assistance and training in learning how to use it. A real example of small to medium sized industry that makes things is the construction industry. We are working with the National Association of Home Builders and the Association of General Contractors in order to include construction elements in the MEP technology transfer centers.

1.2 An Overview of the Advanced Technology Program

James E. Hill
Building and Fire Research Laboratory, NIST

Good Morning, my name is Jim Hill. I work in the Building and Fire Research Laboratory but I am also working part time in the Advanced Technology Program. Dr. Stone asked me to just say a few words to you about the current status of ATP.

Most of you in this room have probably been exposed to this program. Some of you work for companies who have won cooperative agreements from the program. But just to bring everybody up to speed, this is a program that was originally authorized in 1988, appropriated monies for it the first time in 1990, and has been growing rapidly ever since. The mission is to stimulate U.S. economic growth by developing high risk and enabling technologies through programs proposed by industry and cost-shared by NIST and industry.

We have two kinds of activities in the ATP program. We have focussed programs which are described as major research efforts, anywhere from 10 to 50 million dollars a year for up to five years in length. The programs are planned with industry and they're focussed on particular areas of technology. We just started running programs like this in 1994 and 1995. Prior to that we had only general competitions which were an open RFP requesting project proposals from any industrial sector on any area of technology. We continue to run general competitions once per year. But most of the funding since 1994 has been going into these focus program areas.

The way in which the focus program areas are developed is to request ideas from industry and to distill a theme-related focus from those recommendations. In October 1993, NIST Director Dr. Prabhakar told industry what she would like to see in a white paper suggesting areas for focus programs. Almost a thousand white papers have come to NIST since that announcement. In April of 1994, five programs were announced and in November of 1994, six additional focus programs were announced and so at the present time we have eleven focus areas in the ATP program.

I am responsible for the focused program in Refrigeration Technology. It's the only one at the present time that is related to the construction industry. The level of this program over a five year period is considerably less than the other program areas. That's primarily because the construction industry and most elements of the construction industry don't do a lot of research. Perhaps more importantly they don't have a lot of ability to cost share with the government to the extent other industries do.

We have the initial proposals due at NIST in April, so funding of this program will occur before the end of this fiscal year.

The process in summary is that once or twice a year, the NIST Director hears proposals from program managers like myself for focus program ideas. She then selects among all the ideas presented to her and determines which programs to initiate. In about a month, she will receive another series of presentations from us based on ideas that have come in from industry. At that time, we will be presenting an idea for an Advanced Technology Program on Concrete Construction Technology. This is a program that we have been working on cooperatively with the concrete industry for the last nine months.

I do have another group in the industry that is working a bit behind the concrete technology group. They are working on a proposal on Automation Construction Robotics. They've met three or four times since last Fall. They are not quite ready to bring us a recommendation for a program, so chances are that program will be presented to the Director next fall for consideration.

I told you that the ATP program started in 1988 but appropriations first occurred in 1990. The program has been growing dramatically since the first appropriations in 1990. A couple of things are going on right now with respect to the ATP budget. First, there are three rescission bills on Capitol Hill at the present time for FY95. One has passed the House and the Senate. Two others are still under consideration in one or the other bodies. The one bill that has passed, passed the House and called for a rescission of a $107 million of the originally budgeted $431 million. The version that passed the Senate called for a rescission of $32 million of the $431M. They are in conference at the present time and if they can work out an agreement, chances are somewhere between $30 and $107M of the $431M will be rescinded. Our best guess is $60 or $70M.

We've looked at the implication of this possible recission and have decided that we're going to continue with all 11 focus programs the way they've been planned. We think there is enough latitude in the budget in the way the projects were funded to be able to absorb a $60 or $70 million rescission if it occurs.

The President went to Capitol Hill in January with a budget for the ATP program in 1996 at about $490 million. We won't know until September, what is actually going to happen with the 1996 budget. All indications are that ATP is going to continue. It is going to be very healthy; however, perhaps our expectations for budget for the next two years will have to be tempered somewhat. We certainly don't expect anything to happen to this program as has happened to the TRP program -- where they've actually suspended their competitions because they have rescission bills to take their 1995 money back .

1.3 NIST Construction Automation Initiative

William C. Stone
Building and Fire Research Laboratory, NIST

Before we get started, let me introduce a few key people who have helped to organize this workshop. I would like to thank Ken Goodwin from the Manufacturing Engineering Laboratory (MEL), Kent Reed from the Building and Fire Research Lab (BFRL), and Jim Albus and Nick Dagalakis, also from MEL.

One of the reasons that we are here is to see where we might be able to go with future construction technologies. I would like to open with the thought that "It's already been done." And I have a video to prove it. [Brief clip from the 1984 movie Runaway, staring Tom Selleck, showing industrial robots constructing a high rise steel frame building].

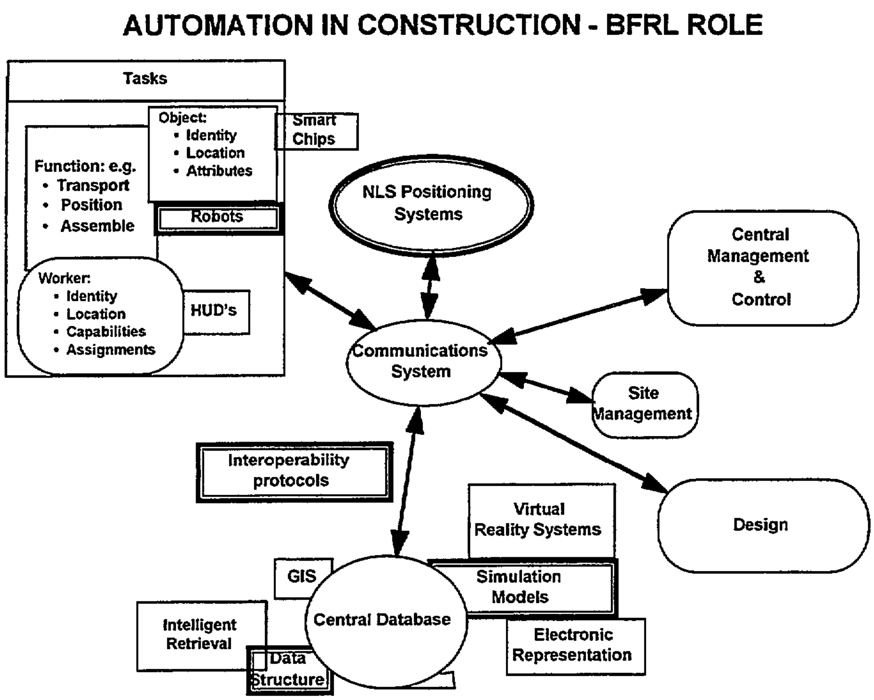
It has been said that Hollywood is always twenty years ahead of reality. The interesting aspect is that this movie was produced 11 years ago. Which means we only have 9 more years, so we had better get moving.

There are many visions that people have had over the years concerning how we might get to that future where the construction process is automated. Certainly, there is an impetus to eliminate dangerous tasks in an arguably risky industry. This is so well known that the Japanese have a saying which captures the essence of the construction workplace: "Kitanai, Kiken, Kitsui" (Dirty, Dangerous, and Difficult). This has secondary ramifications in which the above perception leads to reduced appeal to the workforce to pursue this type of work, which thereby exacerbates skilled laborer shortages and reduced productivity. These latter aspects have motivated such large construction conglomerates as Shimizu and Obayashi to invest heavily in the automation of those procedures deemed kitanai, kiken, and kitsui.

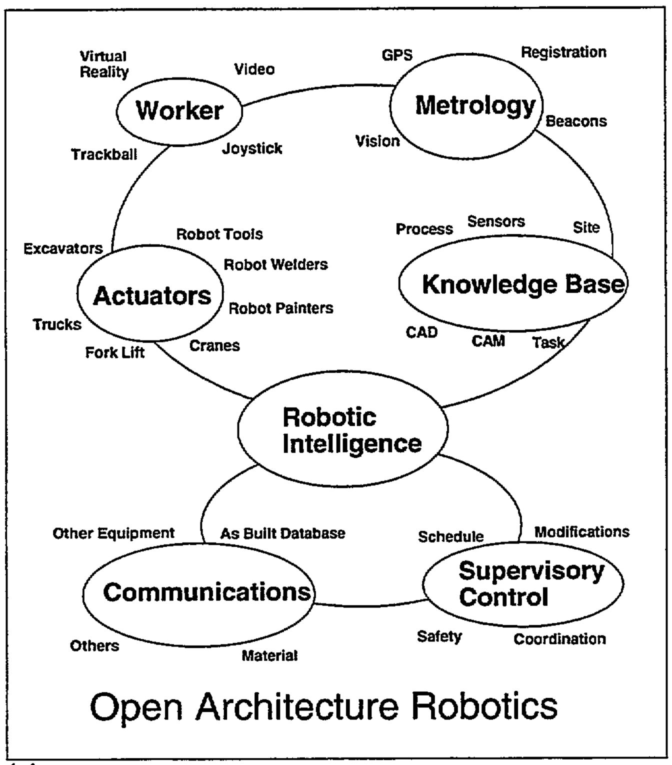
Safety and undesirability aspects aside, construction is an industry which represents 13% of the U.S. GDP and there is significant pressure to achieve greater speed and efficiency in order to remain competitive. Can these disparate vantage points be reconciled through automation?

What we seek, ultimately, are ways in which we can automate various construction processes that are presently manually intensive or dangerous. Equally important, we seek the means to provide up-to-date information to all project participants -- including owners, architects, designers, fabricators, contractors, and workers -- so that delays can be minimized.

People have tried for several years now to come up with possible "architectures" for how we might do this and they all seem to revolve around various common concepts. These include things like metrology at the job site, how you communicate certain pieces of information back and forth, the use of common global databases and processing, and the various ways in which you make use of that information to automate various facets of construction practice.



Figures 1.3.1 & 1.3.2: Two examples of proposed architectures for construction automation



If you organize these topics based on the priority of information you will find that metrology is the common precursor for any form of automation. Metrology in this sense can be loosely interpreted as surveying, but in fact it goes well beyond that. In an automated environment it involves not only the pre-established location of a few control points that establish property boundaries and grade lines, but also the ever changing positions of everything from terrain profile grids, to the location of components and machines in real-time.

Once you have position measurements the big problem is how make use of the data. Presently, most data collected at a jobsite is either manually transcribed or placed in data loggers for subsequent use at the construction shed and back at the main engineering office. Obviously there are time delays between there and the design office. So we are looking at the idea of wireless communications for data transfer.

Construction Automation & Robotics Initiative
Research Program Topics:
• Sensors for Real-Time Construction Site Metrology
• Wide Band Telemetry and Data Acquisition
• Virtual Site Simulation and Object Representation Standards
• Person-in-Loop Systems
• Construction Robotics

Once you get that information, then you have to figure out how to process it. What format should it be in? Who should be able to read it? How should new data be processed? At what update rate? Which processes take priority? Some database interchange standards are already being developed: STEP, ISO, IGES and RTCM to name a few. Many other standards are still needed.

Virtual modeling -- permitting three dimensional computer representations at remote access workstations to visually depict the status at the real jobsite -- is a new way of representing the vast data that would be generated at an automated construction site. In this concept, data gathered at the site could be used, for example, to establish the location of an installed beam or column. The virtual model, given these critical keypoints, creates a photorealistic image of the element within the context of a 3D computer model of the construction site, and displays the beam or column at the location just measured in the field. The same techniques can be used to relay the position, attitude, and articulations of construction machinery, as well as many other defininig attributes including the health of the machine. Standards are needed for how we represent these packets of incoming data so that they can handle the wide variety of categories of measurable data.

Once we have a global database established we would like to return real-time information to various users in a useful format. The obvious immediate users are engineers at the design office who could accept instantaneous representations of the as-built facility in the form of CAD drawings. Such as-built data would also be of substantial valuable to project managers. In our view, however, this is a myopic assessment of the potential possibilities. The real benefits will be gained when the information is turned full circle and provided on demand to a variety of users at the job site, including laborers and machine operators.

The ultimate expression, of course, is semi-intelligent or semi-automated processes at the construction site in which humans and machines complement each others' talents in a manner which is more productive than would be possible using either alone. There are many different beliefs, and predjudices concerning robotics and whether there is a place for this at the construction site. We expect to address this topic today and hopefully dispel some of the myths and clarify what is realistically achievable.

As many of you are aware NIST has proposed an initiative in its FY96 budget in construction automation. Six million dollars per year has been budgeted; what actually happens remains for the Senate to decide. But of the six million, two will be going to Building Systems Automation, that is monitoring systems involved with measuring and predicting the lifecycle process of the building. The remaining four million will go to what we call Process Automation. That is taking the construction of a building from a green site all the way through delivery to the owner and all of the information transfer that goes on in that process.

We've divided process automation into five topics. The one that is receiving early attention is site metrology. This program has been active since last October, and later this morning we'll discuss the kinds of data that have been acquired and where we are heading with this work.

What types of information are of interest from a construction site? We believe that, ultimately, the level of interest will include not only the position of every component, but also the locations of vehicles, and the status of their independent articulations -- for example the state of all of the various moving parts of those vehicles that would be of importantance in assessing the potential for a collision. In other words, if you wanted to use semi-automated vehicles on the construction site, what is the minimum information you need, and at what update rate should this information be provided, to insure the reliability of safety algorithms?

In addition to this, it's my contention that we're also going to have to know where the people are. It may be that we, as a society, are not yet ready for worker I.D. tags, but at least we want to know where people are so that somebody doesn't run over them with a big piece of machinery when they are not within the line of sight of the operator. This is not an idle concern: there was an accident in Pittsburgh about a half year ago in which a surveying inspector was buried one night while an excavating company was working on a new shopping mall. The fellow happened to be behind a large pile of dirt when a big dozer approached from the other side, unaware of his presence.

Real-Time Site Metrology

Technical Goal:

- **Position to 10mm in 3D**
- **Acquisition Time < 1s**
- **Penetrate 50m through Structures**
- **Remote PC interface for Data Uplink**

Knowing where people and vehicles are at all times means tracking in real time. What we mean by "real time" is relative. You may not need to update your knowledge instant by instant for everything at a construction site; only those for which things are changing rapidly. For example if you are placing rolled steel sections with a crane (which might be semi-automated) you want to know on a fairly regular basis what new components have been put in place, and where they are located.

In addition to position, there are other details that might be of interest. For example, you may want to verify the properties of a column or beam and where it was produced, its yield strength etc. This leads to the idea of bar code coding or smart chips which store this type of information local to each component. In addition, it may be desirable to have such information storage tags be of a read-write nature, so that critical time stamps (e.g. date of erection) might be added.

These ID tags would be assigned to all manufactured construction components including things like precast beams, columns and slabs, wide flange steel sections, rebar, wall panels etc. In addition, the orientation of a construction element is of critical importance, which means you have to acquire a certain number of additional key points. For example, the 3D locations of a minimum of three orthogonal points are required to establish spatial positioning of a rigid-body item. How you acquire such data is an interesting dilema which we will talk about in more detail later.

In order to be practical we need to acquire component position to within ten millimeters in three dimensions, and acquire it in less than a second. By way of comparison, you can get one millimeter accuracy over a hundred meter baseline with existing total survey stations equipped with electronic distancing. But there is more. A good metrology system in the automated environment must do three things: a) it must be capable of measuring the three dimensional position and attitude of any component to a reasonable degree of accuracy (which varies depending on the circumstances); b) it must acquire these data fairly rapidly, in some cases with an update rate as fast as 10 Hz; and finally, c) it must be capable of making reliable measurements anywhere on site. Items b) and c) rule out the use of "total stations", since these are designed for point-to-point static precision surveying.

Where you have line-of-sight path, as for example in green field earth moving projects, there are two new, and rapidly evolving technologies -- GPS and fanning laser systems -- that will see use on construction sites within the next few years. We'll be talking a little bit about real-time kinematic differential GPS (or RTK) and what you can actually do with that and finally a few thoughts on pseudolites and where those might see utility at a construction site.

Real-Time Site Metrology

Promising New Technologies:

- **NLS Technologies (SAR based)**
- **GPS Pseudo-lite Emulators**
- **Sub-Centimeter Kinematic GPS**

However, the rub is that neither GPS nor any laser or infrared based distancing system will work when obstructed by even the thinnest of objects. As everyone knows, construction sites are highly unstructured environments -- in contrast with, for example, an automated factory -- and clutter is the norm. You cannot expect to use line-of-sight measurement capabilities for general purpose tracking once structural elements have been erected. But it would be awfully nice -- and simplifying -- if it were somehow possible to measure distances inside a building relative to an exterior benchmark despite the presence of intervening walls. We have a rather unique program underway at NIST to address this topic and will be showing some of the preliminary results later this morning.

Thus far we have discussed measurement systems. But the data for a single position reading are of little value unless it is integrated into an ever changing representation of the complete site. In many respects, individual position measurements can be viewed as independent sensors. In a laboratory experiment it would be possible to connect each position sensor to a central computer via coax wiring and a change in any sensor would be read, nearly instantaneously, by the computer. In this vision a position sensor would be attached to every component and machine at a construction site. However, unlike a laboratory experiment, there can be no wires running around a construction site for a host of practical and reliability reasons. Thus, the problem is how to uplink , via wireless technology, several hundreds of channels of data out of a construction site.

The issues that are of concern are security, fidelity, and bandwidth. Security means that only the construction company, or authorized subcontractors, have access to the data. Fidelity means that the signal to noise ratio is high, despite likely interference in an urban environment, where cell phones, TV stations, and other construction sites will contribute to radio interference. Bandwidth refers to the available frequency spectrum through which data can be transmitted; the wider the bandwidth the greater the potential data transmission rate and the more items that can be tracked in real-time.

The destination for all of the data to be transmitted from the construction site -- and subsequently uplinked via the internet or dedicated fiber optic line -- is a global data management system. The protocol and capabilities of such a global database have seen great attention over

Construction Site Telemetry

Key Issues:

- **Interfacing hundreds of on site positioning systems with global job database**
- **Maximizing real time data reliability (inter-city construction will involve many transmitters at competing nearby jobsites)**
- **Federal Communications law**
- **Data security**
- **Cost**

Virtual Site Simulation

Technical Goals:

- **Develop standard real-time virtual simulation generator tools for construction site management.**
- **Develop standard kinematic graphical representations for construction site objects and vehicles.**
- **Develop modular real-time software to link site data to kinematic response of virtual objects.**
- **Develop Standard Re-configurable machine simulator/teleop training Station.**

the last decade. This morning you will hear from Ernie Kent of the Manufacturing Engineering Laboratory, Kent Reed, from BFRL, and from Mike Simms with NASA, on how we might be able to go about handling jobsite data once we acquire it. Kent Reed will be discussing some of the issues related to standard formatting of the data so that it can readily be used by different hardware and software systems. Given sufficient information, it is possible to create a real time computer-rendered image of what the actual site looks like. This involves the subject of virtual modeling, which will be discussed by Ernie and Mike.

NIST is presently developing a dedicated real time virtual simulation testbed for construction site management that will allow data interchange formats to be evaluated with real construction equipment in the loop. Right now there is no off-shelf software out there that will do this type of task and the hardware must be assembled as a laboratory prototype system. There are many barriers to the practical implementation and common acceptance of such a system. For example, while it is possible to define a machine or component in any number of CAD programs right now, standard formats for graphical representation of construction site objects and vehicles are nonexistant, as is software which makes it easy for for those items to be incorporated into any project planner.

Given component and machinery representation standards we envision a typical manufacturer of wide flange steel sections, for example, having a standard CD ROM containing section details, properties, and ID tags that describe all the manufacturer's products. Likewise, designers and manufacturers of construction equipment might deliver their machinery along with a compatible software representation of the machine that can be used by a generic project planner. The power of such standards lies in the ability to easily and intuitively specify generic standard components and/or machine tasks at the earliest stages of project design. These digital specifications would then carry on throughout the duration of the project and permit ease of tracking as well as progress assessment. One of the things we see as a very useful generic tool within the next ten years is a standard reconfigurable machine simulator which would primarily see use in training and process evaluation, but would also double for teleoperative control in hazardous jobsites. This sounds far off, but there are a large number of common jobsite tasks done today where a high fidelity teleop station would not only allow greater safety, but would actually improve productivity by permitting interactive adjustment of the point of view. The most obvious of these is the operation of a high rise tower crane. The

Person-in-Loop Systems

- **Data Needs at the Construction Site**
  - **Numeric**
  - **Graphics (e.g. blueprints, terrain profile)**
  - **Audio**
- **Human Factors Engineering**
  - **How much data to be displayed?**
  - **To whom?**
  - **How to display it?**
  - **How to access it?**
  - **How to log it?**

approach to development would largely involve integrating military flight simulator capability with a jobsite global database.

As I indicated earlier, we believe that the early payoff in construction automation will be achieved by providing useful processed data, on demand, to foremen, workers, and equipment operators at the construction site. Thus, we are looking at practical means for getting information back to the construction site. We have identified several early candidates. One is the idea that everyone that works on the site would have a very lightweight, hardhat mounted display system that either upon voice activation or some other simple queuing system will give them information that they need to do their job. One example that comes instantly to mind is a component location capability which directs the user to the current whereabouts of the desired part. The technology is usually referred to as a Head-Up Display (HUD) or Helmet Mounted Display (HMD) and we actually have some hardware here that will be demonstrated by Ron Levondowski from Honeywell. These are being developed for the military right now. The analogy to the construction industry is readily apparent.

Person-in-Loop Systems

Technical Goals:

- **Develop Helmet-Mounted (HMD)"Database Interrogator": direct info to average construction worker.**
- **Develop HMDs and/or projection HUDs for Graphics-Based Feedback for operator-controlled construction equipment.**

We also want to provide on-demand information to vehicle operators. In the context of construction operations these would include machine specific feedback for everything from forklifts to dozers, backhoes, and cranes.

This now leads into the issue of human factors design. For example, how do you display the information, what is the least amount of information you really need, what tasks will you allow to be semi-automated etc.. The engineering questions largely reduce to the nature and amount of data that will be transmitted to the vehicle operator. The human factors side says, "We can give you all the data you want right now, but can you use it effectively? There are a lot of people who have experimented with head-up displays before and you know that if you have a constant red blinking light out there that's trying to tell you that the system has a fault, people will simply block it out of their mind if the machine continues to work and whatever fault was detected is not affecting the equipment. Those are some factors we must eventually deal with in terms of making information effective when it is delivered to the job site.

Finally, I would like to say a few words concerning construction robotics. This involves the idea of either fully

Construction Robotics:

What is Futuristic ?
What is Achievable?

- **Turning loose a 1000 horsepower machine or a 50 ton crane on a construction site without human supervision is <u>not</u> likely in the foreseeable future.**
- **More likely: full time operator does the set-up, fixturing, initialization, and choice of process to be performed.**

Construction Robotics:
Guiding Philosophy

- **Let the OPERATOR do what is easy and natural for a human.**
- **Let the COMPUTER do what is easy and natural for the computer.**
- **Machine-Operator TEAM may be 5-10 times more productive than conventional methods.**

autonomous or semi-autonomous operations at a construction site. You saw a little bit of what that might look like in the Hollywood film. The real question is, "what is reality -- what is really achievable." Jim Albus was asked this question a while back and he came up with what I thought was a rather memorable quote: "turning loose a thousand horsepower machine or a fifty ton crane on a construction site is not likely within the foreseeable future without human supervision."

Construction Robotics

Technical Goals:

- **Down select of most desirable construction task candidates for automation**
- **Initial Demonstration Project in semi-automated robot operations (on site setup by construction personnel; autonomous task execution by the robot)**

My suspicion is that the American Trial Lawyers Association would also advise you that this would be a prudent course of action. The hybrid scenario involves the operator doing the task set up for a software reconfigurable machine that can do several jobs. The idea is to let the operator do what is easy and natural for a human and let the computer do what is easy and natural -- repetitive, precisely repeated tasks without fatigue -- for a computer.

What we're hoping is that the combination will be much more efficient and productive than either man or machine. At NIST, we presently have no projected budget under this topic. The reason is that we feel these are going to be applications specific. Our intent is to focus on the common underpinning technology first, and in the meantime develop a prioritized implementation list where semi-autonomous tasks might yield high early payback.

1.4 Real-Time 3D Laser-Based Positioning

Eric Lundberg
Spatial Positioning Systems, Inc. (SPSI)

Thank you, it feels great to be here. This is probably the most receptive and interesting audience I've ever presented to. I'll give you a little history. SPSI has been thinking about construction automation for quite a while. We see the issue with site construction as being one of information delivery and how you go about doing that. Other industries, such as manufacturing, and certainly office automation, have come a long ways over the last twenty years in the implementation of computers into the workplace.

In particular the special issues pertaining to construction are: how do you process information and how do you display information? These really haven't been addressed by the construction industry, and it is along these lines that I want to talk to you today.

The presentation will be divided into three sections. We are going to talk about what we're currently doing at SPSI, what products we actually have out now that are being implemented on construction sites and how these relate to the goal of implementing computers and information delivery onto the job site; we'll look at what we expect to be doing over the next few months; and then discuss what we see as the future and where SPSI will be heading in the next few years.

We produce a laser position measurement technology with the product brand name "Odyssey." It is a very accurate, quick, 3D position measurement system that requires line-of-sight viewing and can work down to millimeter level positioning accuracy. It can provide update rates anywhere from five to twenty-five times a second. We have a software package that rides on that. It gives basic functionalities to the construction user such as distance between two points, volume, area, that type of thing. It can be used by a cross section of construction crafts people and inspectors to augment their jobs and tasks.

Our system uses a group of laser transmitters. The fundamental principle of the technology is the mathematics of intersecting planes and the fact that three planes uniquely define an intersection point in space.

The implementation is different from standard surveying technologies. We use two sensors on a positioning receiver rod, and we determine the position of those two sensors independently. Because of this, the positioning pole can be held in any orientation. This removes a major source of error associated with standard surveying and there is the additional benefit that the operator is reading xyz coordinates in real-time. So, as quickly as the operator moves the measurement pole he gets an instant update on where that sensor is and exactly where the reference point is.

The other product that we have is a software product. It integrates that xyz coordinate into a CAD model. You can now uplink position information to a local PC and see where you are relative to the site CAD model. Surveyors can now graphically lay out where they are directly from your CAD models, as opposed to doing things from blueprint drawings. This software has been written to work with a variety of computer-based position measurement tools, including total stations and GPS. We are using the Odyssey technology primarily for assessing the as-built status at a construciton site.

Within the the next few months, we expect to begin work in the equipment control area. Part of the issue that Bill pointed out was that you need to know where pieces of equipment are on the job site. It is very difficult when you think how it is currently done: operators look at grade stakes and estimate a high or low of where they need to be. It's very time consuming and very repetitive. You have to work, survey, re-work, and survey again until you reach some sort of tolerance that's acceptable.

One solution to this dilema is to provide a CAD display in the vehicle cab which continuously compares the instantanous vehicle position with the CAD design file and allows the operator to get it right the first time, every time, so he actually knows where he is all the time.

In about six weeks we'll be delivering a system down to North Carolina State University where it will be hooked into an excavator [by Leonhard Bernhold's Construction Automation and Robotics Laboratory team]. One thing you might want to think about for a bull dozer, for example, would be to display the design grade and indicate where you have to cut or fill to make that happen. These graphical cues would be updated in real-time and would relate exactly to the present vehicle position. Another example where this might be very useful — and this certainly has some interesting safety implications —would be to display where underground obstructions might be and display exactly where the bucket, in this case of an excavator, would be relative to those obstructions.

There was an interesting incident that happened at the beginning of the year at Newark Airport. A construction crew dug up the main power cable going to the airport. The airport was completely shut down for a substantial period of time. This underscores that knowing where you are can have a potential benefit not only to the efficiency of the construction operation, but also to those affected by accidents and mishaps at the construction site.

The other thing we are looking at down the road involves the establishment of position measurement, CAD integration, and position control technology on the job site as a utility, much like electricity. It would be set up by the construction manager and anybody who had the proper tools for their job would be able to use that information to help them in their work.

As an example, let's say the construction manager is using our Odyssey system. He would be responsible for setting up the transmitters and doing the calibration and providing any information to the sub-contractors or the specialty contractors who would have their own specialty computer-aided tools and in particular their own software. They could then integrate the position information coming from the site control. The concept is that everybody would be working off the same baseline, yet would have specific tools that would help them in their specific jobs.

Where do we think we might be going? I'm glad Dr. Stone set the stage for this. The last time I presented these virtual reality slides — about two years ago — it created such an uproar that I wasn't even able to finish my presentation. But, I see that we have a much more receptive audience this time. One of the key requirements to enabling virtual reality is a position measurement system. The way I perceive virtual reality is really nothing more than another type of display. Here I am referring to a flat panel display used to create a stereo image that somebody can use.

Right now, there are off-shelf virtual reality positioning systems that allow you to work in VR within a very small volume. These are basically laboratory R&D systems. With our system you can work over hundreds of meters. This opens up VR for the construction industry as a site tool. Imagine for the moment that we are building a 2x4 wall and we are presenting a registered image of the 3D design on a heads-up display to a carpenter. This projection would most likely be a wire frame. The carpenter will be able to see right through the wire frame and sense, through the image, where the actual wall needs to go. The task then becomes one of placing the real object where the virtual image is. You can very quickly speed up the process of construction with something like this.
Not only would it be invaluable to a site worker, but also an inspector could quickly see even in this simple example if anything was misaligned. Now, where can you go from there? There are a lot of new technologies today that can be utilized on the job site. There's video, mass data storage, high speed communications, networking — all with information delivery and communications capabilities. The ultimate construction worker might one day in the not too distant future carry all of these on his person.

The heads-up display now takes on even greater importance: it could be used to provide education video on demand. Let's say that I'm working in a particular area or doing a particular task that I'd never done before but instead of asking somebody, I communicate back to a server that displays a small video to me. Maybe a quick five minute learning tape while I'm out in the field. With this I see what is going on and now I have a window that pops up and instructs me step-by-step on how to do that particular task.

We believe that individual voice communications will become ubiquitous, much like we have walkie talkies today, but with the capability to interface to voice activated software. Equipped with such communications, I would also be able to find anybody on the job site or maybe even anybody in the company if I needed their help right away. Of course the ideal communications system could display not only the data, but voice and video at the same time. So our super construction workers would not only be able to communicate amongst themselves but also to a job site-wide information network, where everybody can communicate with anybody else in real time. This would effortlessly permit coordination of tasks and also would improve safety quite a bit.

You can take this concept one step further to where a whole company can be integrated together, where experts and construction managers might no longer even need to be at the job site. With the level of immediate, first hand information they could get from the crafts people and the people at the job site they could actually be in the main office and still be highly effective. Likewise, experts and particularly good problem solvers could be located anywhere in the company and through this universal communications system would be able to communicate with those people who needed the expertise. That, in a nutshell, is our vision, and a roadmap of where we're going to be heading in the next few years. Thank you very much.

Group Discussion

Chuck Schaidle, Caterpillar: *How do you tell where all of these cables are under the ground?*

You have to model them as you put them in. It's kind of an ongoing thing. As you build things you have to create as-built models. At least, that's what you would have to do if you were solely doing it using our system. There are certainly technologies out there now that sense things under ground but you have to have the as-built models somehow prior to what I was presenting here.

Jim Albus, NIST: *What about existing plants. There are no accurate as-built models. Are you working with any technology to sense the size of something underground and can you then add that information to the as-built drawings for a project? Are you working with anything that can sense the size and shape of buried components?*

We are not working on that specifically, however, we do know of companies that are. They specialize in figuring out whats underground. And you could tie our position measurement technology with their remote sensing technology to get your as-built models. But its a tough way to go, to go back after the site has been covered up. I think what needs to be — and I think is starting to become the philosophy in construction — is to actually create the as-built drawings as you are building and create that computer data base for the future. Look ahead, knowing that someday I am probably going to come back here and have to dig around. Unfortunately, this has not been done on 99% of the projects that have been built.

Ken Reinschmidt, Stone & Webster: *We are finding that clients do not want to pay for as-builts, especially things that are above ground.*

They want to or do not want to?

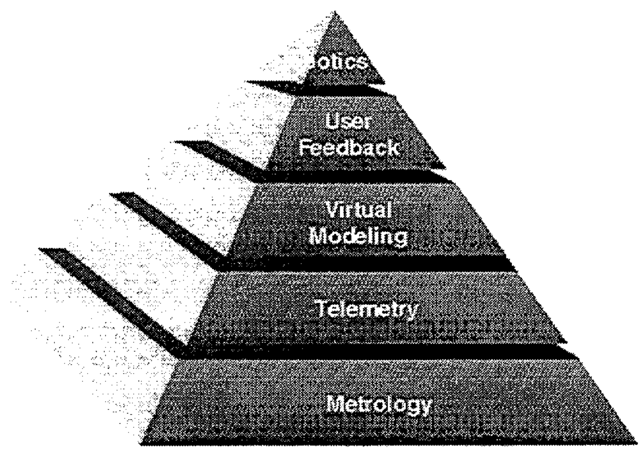
Ken Reinschmidt, Stone & Webster: *They do not want to pay the money for as-built* *drawings for items that are above ground and can be plainly seen. They can go back and digitize that. One thing that we are working with right now is the pen pad computer. And in particular the Toshiba pen pad unit, because up to now you can get it with a passive color monitor.*

1.5 Real-Time GPS & Non-Line-of-Sight Metrology

William C. Stone
Building and Fire Research Laboratory, NIST

I would like to pick up where Eric left off and describe the results of research which is currently underway at NIST in the field of construction metrology. Earlier I indicated that there were many technological steps along the way to implementing the real benefits of automation at a construction site. The underpinning of all of this is the need to know where things are. In the past this need has been met (in a minimal way) by static benchmarks and survey stakeouts provided by field crews. Even with digital total stations and laser or infrared-based electronic distancing, this is a slow and tedious process. And it must be repeated many times during the course of a construction job as the geometry of the worked terrain changes.

In looking forward to automation, we find that there are two needs which demand new methods of measuring from that used by the traditional surveying crew. First, there is a need for timeliness of data. This will vary from as slow as perhaps once or twice a day for the position of key components to as fast as 30 times a second for the control of machinery. Secondly, there is a need to track not just a few benchmarks, but *anything* that moves on the construction site. Initially this will involve the tracking of the movement of components in order to establish the as-built status of of a project. But it will quicky progress to autopilot systems for earthmoving machinery, cranes and other mechanized units, and to component locators and registered-view helmet mounted displays that provide information on where to set out an item without the need for any other form of measurement. What is needed to permit this is a dynamic sensing system that provides rapid updates of position to the levels of accuracy needed for construction.



Construction Automation Hierarchy

One approach, developed by SPSI and others, involves rotating fanning lasers. Another that has been receiving a great deal of attention lately is GPS, the satellite-based Global Positioning System. There are a number of reasons for this attention, but perhaps the most important ones are that it requires no prior setup at the site: each vehicle or surveyor, provided they are in view of sufficient satellites, can determine their own position independently, anywhere in the world. And, in a sense, because the satellites are "overhead", it has less of the problems with the requirement for direct line-of-sight that rigidly control the capabilities of laser, infrared, and optical measuring systems. But it does have its own limitations in this area.

Earlier this year we carried out a program, using the most accurate GPS system we could obtain, in an effort to develop an un-biased set of measurements that would answer two questions: 1) what is the level of accuracy that can really be achieved at this time, and under what conditions? and 2) what are the limitations of this technology relative to its use for replacing traditional surveying equipment at a construction site?

Although most of us have heard of GPS, the majority who have are not aware of the various levels of performance and accuracy that are inherent in the system. At this point I would like to give you a brief description of the system and then a discussion of the three levels of accuracy that we were able to obtain during the course of extensive tests carried out on the NIST campus, which, incidentally, is home to the National Geodetic Survey GPS Test Range... so we can lay claim to a few of the most heavily surveyed benchmarks in the country!

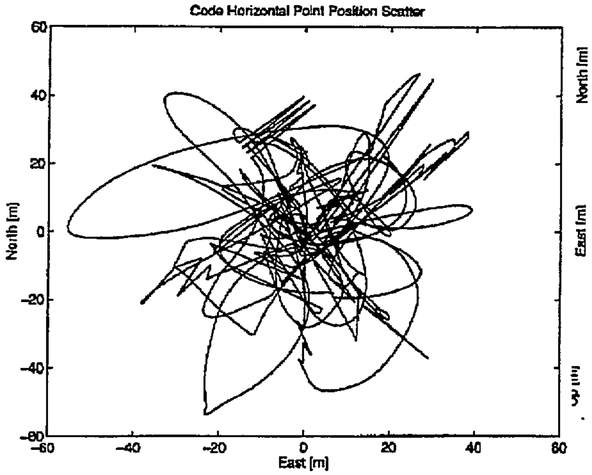
The fundamental navigation technique for GPS is to use one way ranging from the GPS satellites which are also broadcasting their estimated positions. They do this by sending a coded signal which modulates the carrier frequency broadcast by each satellite. Each satellite has its own unique code. Ranges are simultaneously measured to four satellites (or more) in view by matching (correlating) the incoming signal with a user generated replica signal and measuring the received phase against the user's (relatively crude) crystal clock (Phase information is transformed into time-of-flight and therefore distance). With four satellites and appropriate geometry, four unknowns can be determined; typically, they are: latitude, longitude, altitude, and a correction to the user's clock.

Given these broadcast signals, there are three basic methods of determining position. The simplest of these is known as the *Code Solution.*

Code Solution

The primary intent of the GPS system was to provide 5 to 10 meter accuracy absolute point positions for the U.S. Department of Defense. Data is sent from the satellites to potential users on two distinct frequencies, each with a different format. The high-accuracy service is called the Precise Positioning Service (PPS) and uses what is called P-code (Precise-code). The use of PPS is restricted and is not available for civilian use when Selective Availability (S/A) is turned on.

A lower level of precision is available at all times and is called the Standard Positioning Service (SPS) which uses the Coarse Acquisition or C/A-code. In this, a short pseudo-random noise code is broadcast at a rate of 1.023 megabits/second and contains satellite position and time. Because of it higher modulation bandwidth, the P-code ranging signal is more precise. This code , when encrypted, becomes the Y code. The military uses this encryption capability in such a way as to prevent the more precise positioning service from being used by an unauthorized user. During S/A the satel-



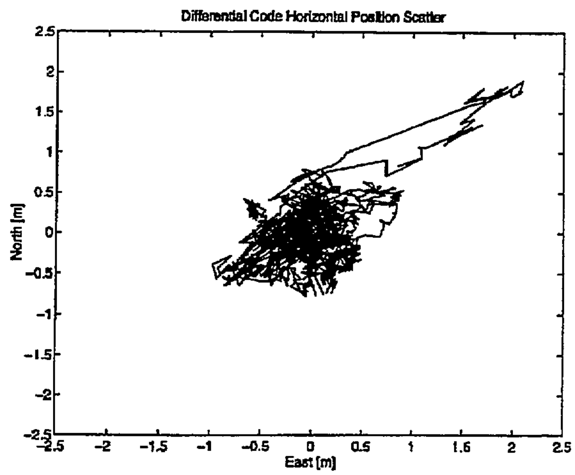
lite frequency is dithered, limiting the point position to an accuracy of 100 m in the horizontal and 150 m in the vertical components.

An example of the variation in position using SPS with S/A on (above figure) is shown for 2.5 hours of data collected using a Trimble SSe receiver. During this period the position varied up to 50 meters horizontally and 100 meters vertically.

Differential Code Solution

Considerable improvement can be obtained by combining observations from two receivers; the second unit comprises the "reference" receiver. If they are relatively close to each other, both receivers see essentially the same range error to each satellite and corresponding error in position. With one receiver at a known position, the range errors can be determined and transmitted to the roving receiver. The roving receiver applies these corrections to the observed ranges in real-time. The standard format for code differential corrections is RTCM. Almost all GPS receivers with a serial interface are capable of accepting RTCM corrections. For small inexpensive receivers (~$300), the accuracy is limited by the noise level of the code measurement which is typically 2 to 10 meters. A newer class of enhanced C/A code tracking receivers such as the Trimble 4000 SSe and Ashtech Z12 have noise levels at the 0.5 meter level and advertise 1 meter level differential position accuracy.

A pair of Trimble 4000 SSe's were connected using a radio link with one set as a reference station and the other to accept RTCM corrections. The results are shown

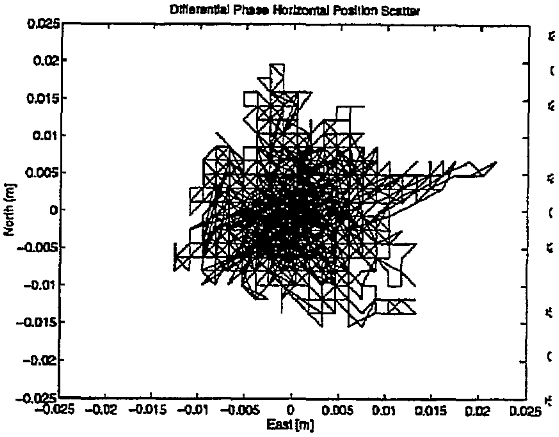


in the figure below. The majority of the horizontal positions differ by less than +- 50 cm with the exception of a nearly 2 meter horizontal excursion near the start of the time series. The vertical solution variation is up to +- 5 meters but more typically less than +- 1 meter.

The precision of the differential solution using only C/A code will degrade with increasing distance due to ionospheric effects, tropospheric effects and errors in the broadcast orbit ephemeris. Current development is directed toward increasing the range of code differential GPS (DGPS) beyond about 100 km. From a software point of view, the techniques are relatively straightforward and the reliability is high.

Phase Differential Solution

The highest degree of position precision is obtained using carrier-phase data. The receiver noise level of the carrier phase measurement is approximately 1 mm as opposed to about 50 cm for the better C/A code receivers. The carrier phase noise level typically increases to about 1 cm or larger due to multipath. Geodetic-quality GPS receivers recording both L1 and L2 carrier phase measurements and static surveys (many hours of data at a fixed point) can achieve mm- to cm-level precisions on base- lines up to 1000s of km in length. The difficulty with using carrier phase measurements is that, while the fractional phase can be determined to high precision, there is an inherent initial integer cycle ambiguity. The integer number of cycles of the carrier phase must be determined where a cycle is 19 cm in the L1 and 24 cm at the L2 frequencies. With static surveys, the initial ambiguity is estimated along with the coordinate solution, using as much continuous data as is available. For short breaks, called "cycle slips", the fractional phase is recovered when tracking resumes, but the integer cycles is lost. Cycle slips can usually be corrected in preprocessing for over short gaps or



when the loss does not occur to all satellites at once. Over longer gaps cycle slips cannot be uniquely determined and new ambiguities must be estimated.

Typical phase differential accuracy obtained during the NIST tests is shown in the figure above, which represents the response measured atop a fixed benchmark. Accuracy over an approximately two hour sampling period was +/- 20 mm. Drift over a short period can be significantly less.

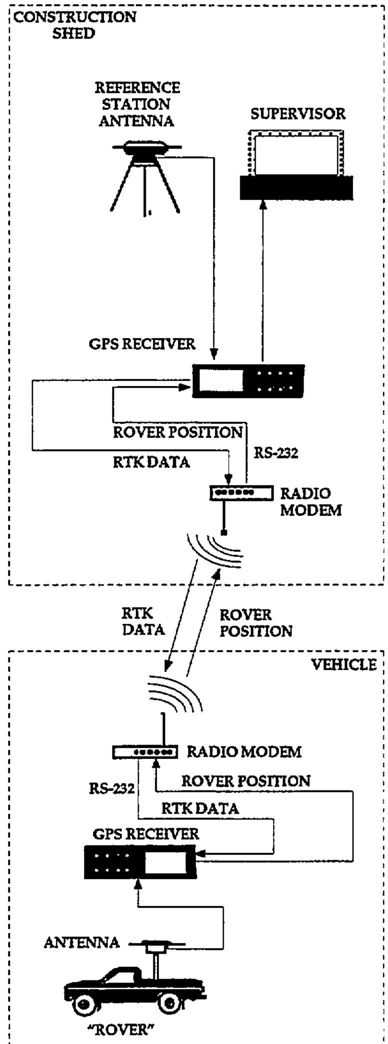
RTK Tests

The use of GPS carrier phase data for determining continuous cm-level relative positions for stationary or moving platforms is called "kinematic" (RTK) positioning or surveying. We recently conducted a series of tests using a roving platform based on an instrumented HumVee (see photo below) that was loaned to us by Jim Albus's group working on autonomous vehicles.

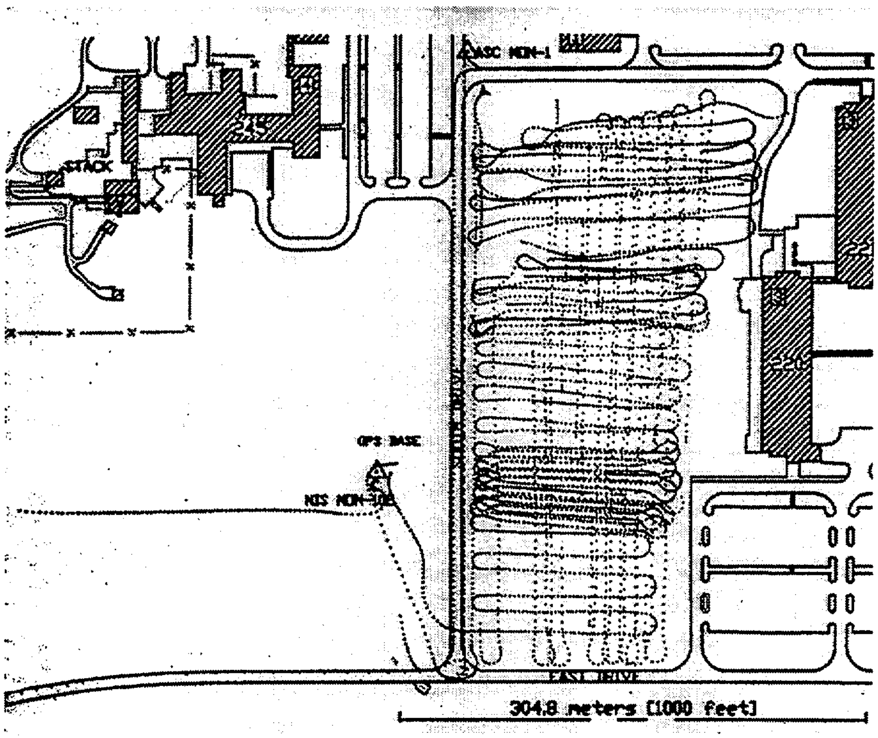
The actual RTK instruments were a pair of Trimble 4000SSe receivers with real-time kinematic (RTK) and on-the-fly ambiguity resolution (OTF). Others GPS receiver manufacturers, including

Ashtech, Novatell etc. supply similar units. The GPS receiver units are linked by means of a radio modem. A wireless ethernet system could have been used equally well within the kilometer square test course we laid out. The reference receiver was stationed atop NIST monument 102 while the roving receiver was placed on the instrument support frame on the HumVee. The base station transmits the RTK ambiguity resolution data to the vehicle and the vehicle transmits its corrected position back to the base station, where it can also be picked up and monitored, for example, at a supervisors construction office. The basic architecture is shown below:

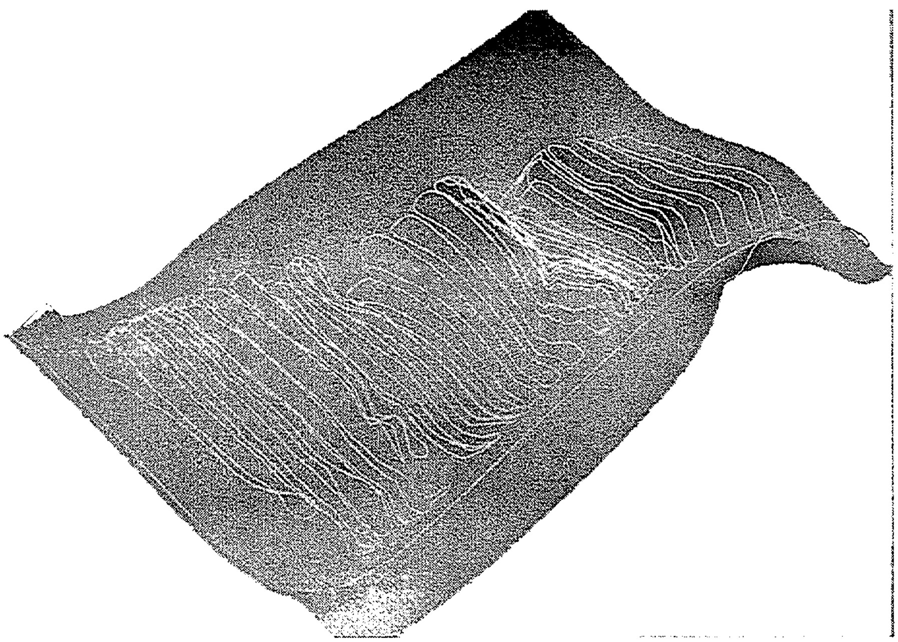
We conducted a number of RTK experiments. Some were conducted along the roads, others involved topographic mapping of a field. The road tests showed good agreement between the NIST AutoCAD database -- and at speeds of 20-40 kph, there was no loss of data and the recorded data lay correctly on the road traces. High acceleration to 60 kph caused loss of satellite lock which did not reinitialize before the drive was over (approximately a 1.5 km course)



An analysis of the data gaps showed two types of breaks. The first, a complete loss lock to the satellites, required reinitialization either statically or on-the-fly. These breaks lasted on average about 120 seconds. A shorter type of break was caused by a break in the ground receiver-to-receiver radio link either on the outgoing or incoming side. This was caused (at different times) by building, terrain, or foliage interference. The average break in these cases was only 14 seconds. These results highlight the need for more rapid reinitialization or the need for alternate navigation methods (such as inertial or magnetic systems) when

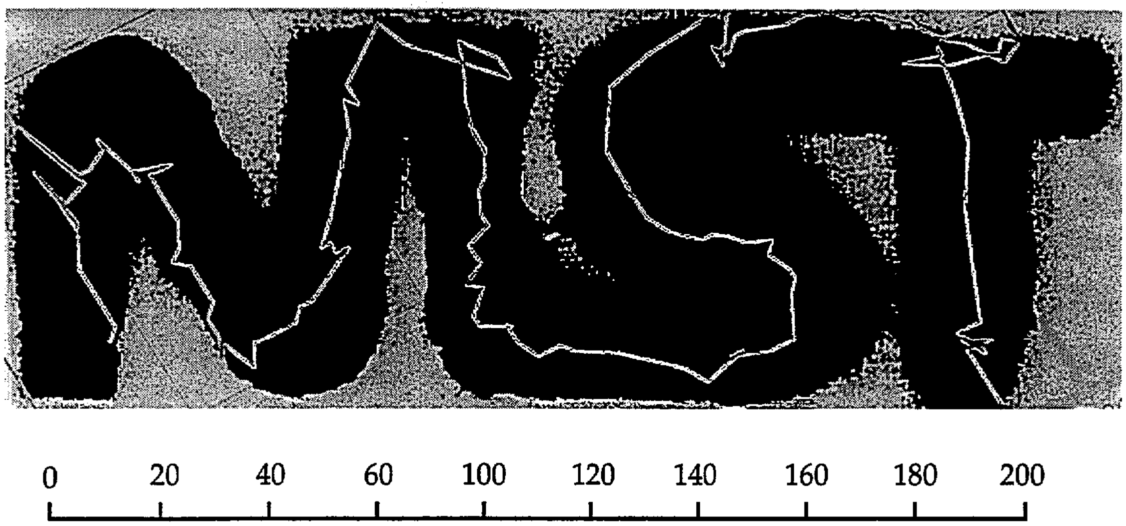


Above: Ground trace of HumVee superimposed on AutoCAD site map. NIST Monument 102 served as the known location for the base receiver.
Below: Transformation of the GPS RTK data into a 3D surface model. Only North-South ground tracks are shown for clarity.



moving vehicles and machinery are involved. It is of some interest to note that driving the HumVee under light foliage was also sufficient in most cases to cause either a fall back to pure code solution or a complete loss of satellite lock. This can be considered a direct consequence of the line-of-sight limitations of GPS. Similar loss of lock was observed upon approach to tall buildings which obscured critical satellites, and, as alluded to before, high (vehicle) accelerations. In many cases these high accelerations could be obtained through rapid turns within 50 m of nearby buildings. In open fields, we were able to maintain phase lock while pulling the tightest turn possible with the HumVee (about an 8 m radius) at 40 kph.

The topographic mapping results using RTK were used to generate contoured maps with an interval of 50 cm over a total terrain vertical differential of only seven meters. A detailed analysis of the intersecting points showed the vertical differ-



Above: Results of precision GPS positioning: penmanship test with differential phase RTK tracking. Scale is in millimeters.

ence of crossing tracks was no worse than ± 10 cm and had a standard deviation of only ± 3.7 cm. The intersections were only approximate and did not include a correction for the attitude of the vehicle, but still clearly demonstrate the vertical precision of the RTK system. Again, the loss of lock was quite evident when the vehicle was moving and there clearly is need for rapid OTF reinitialization or backup navigation systems.

Scaling the tracking to multiple vehicles would require additional development at the tracking site. Supplying the RTK corrections is not a problem with more receivers. A single reference receiver can broadcast on the same frequency and on a one-way link to an unlimited number of roving receivers. Each receiver performs it's own RTK calculations. The challenge will be to simultaneously return the positions to the tracking/monitoring site.

As a final, and perhaps more graphic, test of RTK precision, the rover antenna was placed on the top of a pencil and the operator traced out the letters "NIST" by hand (see the **above** figure). At 1 second sampling the writing took 1.5 minutes to complete. The letters are easily distinguished. Slight imperfections reflect in part the measurement noise and in part the limits to how steady the operator can hold the pencil/antenna while trying not to block the satellite signals. The individual letter line thickness is approximately 10-12 mm. The smaller scale lines which have been superimposed are at 10 mm spacing. These suggest that for this short duration test the accuracy of the trace, including all error terms, was approximately +/- 5-6 mm, since the traces lie within the letter line thickness. These tests gave us a feel for what can be done with present off-the-shelf commercial GPS receivers.

Obstacles to using RTK GPS for Construction Metrology:

A number of factors limit the degree to which this technology can be introduced into general construction.

• **Cost:** The units which were used for this study sell at a retail price of approximately $100,000. While this may in some cases be justified for certain extremely expensive machinery where opportunities for full automation are evident (as for example in open pit mining) it is not within reach of the majority of contractors. Those receivers that are within reach are typically pure code receivers with at best, differential accuracies of 5-10 m. What is needed is a standard, low cost differential phase receiver with an open architecture, such that it can be produced by many competing companies, in much the same fashion that IBM made public the architecture for its first PCs. The alternative is to wait and hope that potential demand for GPS based differential trackers for the automobile market will lead to the economies of scale that would permit a radical drop in receiver pricing. In the automobile industry a, "feature" like GPS would not be added unless the option-cost were on the order of $500-1500.

• **Loss of Signal Lock:** Frequently during our moving vehicle tests, we lost either phase tracking lock or differential RF signal. Such periodic loss of position will be unacceptable to construction companies which will be counting on that data to drive semi-autonomous or fully autonomous vehicles. Bringing the vehicle to full halt every time signal is lost -- either due to multipath, excessive acceleration, or line-of-sight blockage -- is at best costly in machine downtime, and at worst may occur in the middle of a critical operation, such as the hoisting, placement, and mating of a 100 ton lift. Economical methods need to be investigated for dealing with loss of GPS lock. An obvious solution is to use an onboard inertial guidance system, and use GPS to provide frequent updates on absolute position, but inertial measurement units (IMUs) are not cheap either. Another possibility is the development of economical pseudolites which could be distributed throughout the construction site to insure local coverage within a specified work zone.

Attitude Acquisition & Other Sensory Feedback:

In many cases, position alone will be sufficient to meet construction site metrology needs. That is, coordinates of a point in 3D space. This is most obvious for determining the location of a particular structural component. For vehicles this is not enough, since the yaw, pitch, and roll of the vehicle, relative to the positioning receiver will affect the interference geometry of the machine (will it hit an adjacent concrete wall when the boom swings around) as well as the location of various parts, including articulated appendages. Attitude (yaw, pitch, and roll) can be determined by GPS, provided a multiple antenna array is included. The angular accuracy is limited by the GPS absolute positional accuracy divided by the baseline arm between orthogonal sets of antennas. It could also be done by means of a pair of digital clinometers and a soft iron compensated digital flux gate compass. A generic strap-down status unit will be needed to relay these six pieces of information as well as other data that describe both the full kinematics of the vehicle. In addition vehicle health monitoring diagnostic data such as engine temperature and pressure, hydraulic pressures etc., may also be included.

Thus far, there has been no effort to develop a standard for data interchange from such a strap-down "black box". But to progress towards a "plug-and-play" approach to integrating partially or fully automated machinery into the construction, such a standard will have to be developed and accepted by the various industry participants.

Non-Line-Of-Sight Metrology:

There are significant limitations to line-of-sight (LOS) position metrology. I would now like to discuss some of the nascent experiments conducted at NIST which are leading towards the development of what we refer to as NLS (Non-Line-of-Sight) metrology.

The problem of eliminating the line-of-sight requirement while achieving high precision in real time is a difficult one. All of the systems previously described above rely on the use of high frequency radiation (UV laser light in one case, and mid to high band RF in the others) which have the unfortunate characteristic of near-total dissipation when encountered by objects typical at most construction sites -- for example, a brick, masonry, or concrete wall... or even paper.

In order to survey through engineering materials a different approach must be

NLS: Non-Line-of-Sight Metrology

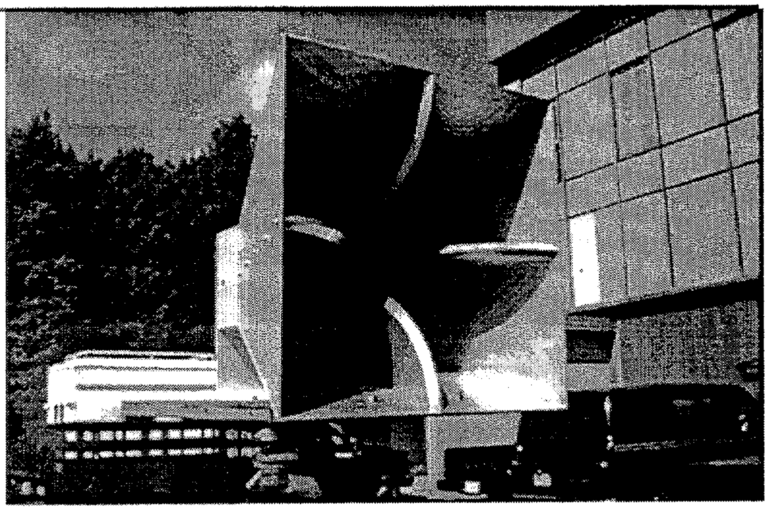
- **Fundamental Principles**
  - **SAR Based Technology**
  - **Hit Structure with many discrete wavelengths**
  - **Process (DSP) combined response of 1000's of individual Frequency Domain Frequencies; Resolution = c/B**
  - **First arrival peak in Time Domain signals shortest time-of-flight = Distance**
  - **1 nanosecond = 1 foot = 0.3048 m**

Construction Automation & Robotics

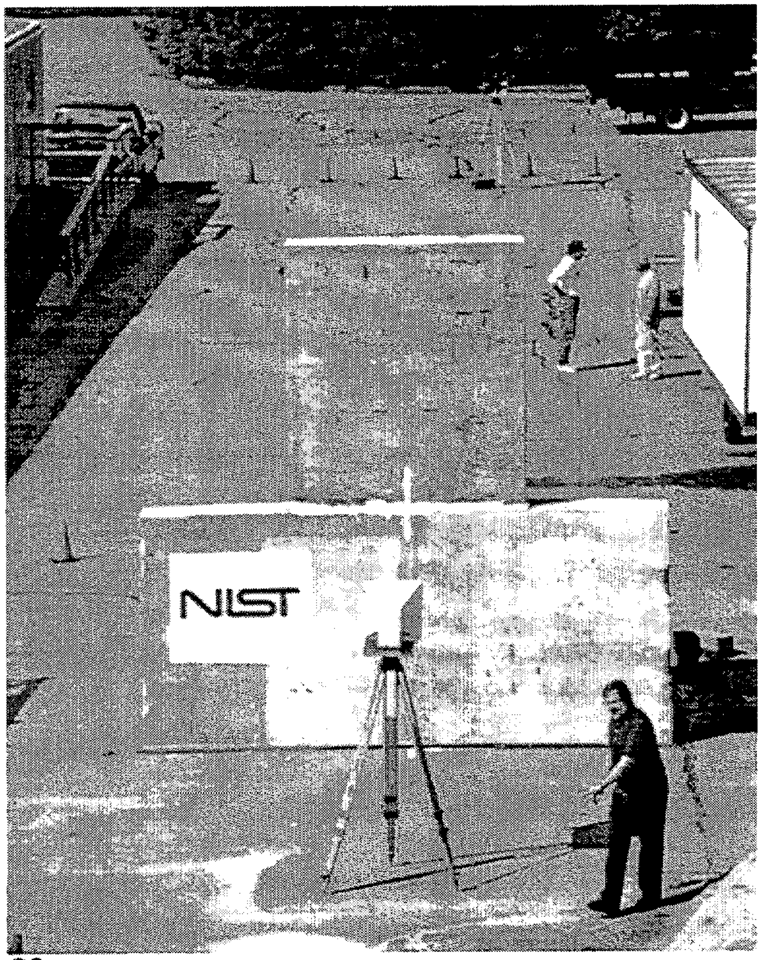
used. The approach we have developed makes use of ultra wide band transmission techniques, which are sometimes referred to as "impulse radar", "spread spectrum radar," and "base band radar." Prior work with these technologies appears to have been directed to surveillance, where it was not possible to have a "cooperative" receiver on the inside of the target structure. Fundamental work remained to be done with cooperative receivers to determine which part of the E-M spectrum is most effective in penetrating engineering materials.

The experimental NLS program was initiated at NIST in cooperation with MIT Lincoln Laboratories. The objective of the preliminary laboratory investigation was to determine the effectiveness of spread spectrum radar transmissions, with a bandwidth of 1.5Ghz (from 500 Mhz through L-band (2 Ghz)), to penetrate various engineering materials and structures and to locate a "cooperative" positioning receiver beyond such obstacles.

Preliminary results show that it is possible to locate, via time-of-flight measurements, the position of a receiver beyond a meter-thick reinforced concrete wall, or



Above: Watkins-Johnson Quad-Ridged Horn antenna used for NLS tests at NIST. Frequency range is 0.5-26 GHz.
Below: Building 226 Test Site. Transmitter is located 50 m behind a 500 mm thick reinforced concrete wall; receiver (bottom of photo) is located 5 m in front of the wall.



beyond several brick and masonry block walls, and beyond typical interfering stacks of wide flange girders.

The transmission and receiving antennae, which in normal radar are typically one and the same, were physically separated so as to create a system with a fixed broadcast unit and a "roving" receiver, whose range was to be determined relative to the transmission antenna by means of time-of-arrival measurements.

Time domain response was synthesized by means of chirp-z Fourier theory from a broad spectrum of data sampled in the frequency domain. Numerous field experiments were performed in which typical construction site obstacles were placed between the transmitter and receiver with separation distances of up to 70 meters. The obstacles included a half-meter thick, heavily reinforced concrete wall , varying combinations of masonry block and brick up to more than a meter in thickness and at varying angle-of-incidence orientations relative to the transmission path, and metal pre-fabricated wall panels. In all but the latter case repeatable distance measurements were obtained. Range detection was lost in the presence of extensive metal panels which contained no windows.

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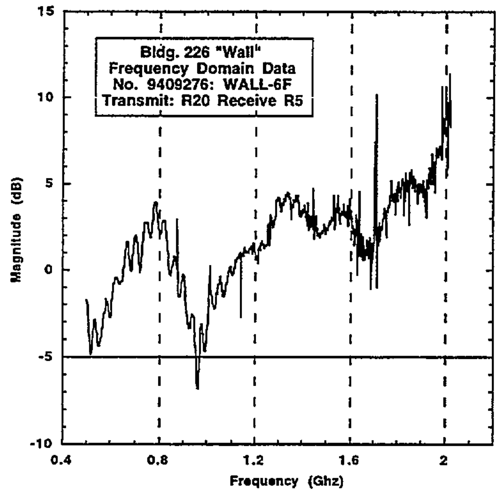
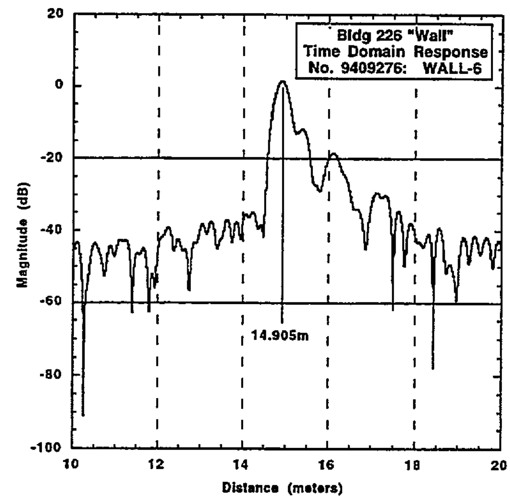


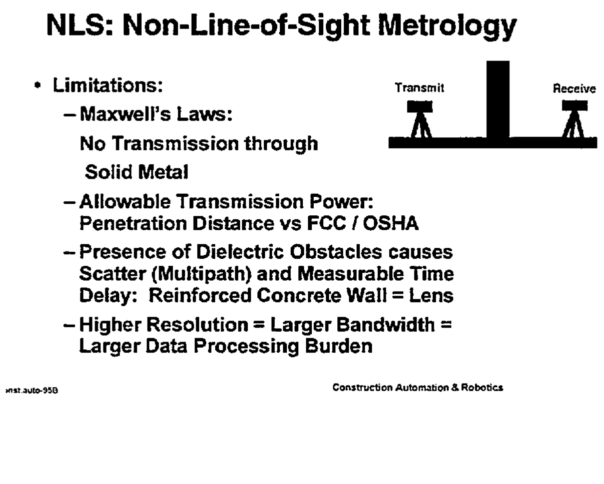
Above: Frequency domain response for a spread spectrum radar signal penetrating a 500 mm thick reinforced wall (see opposite photo).



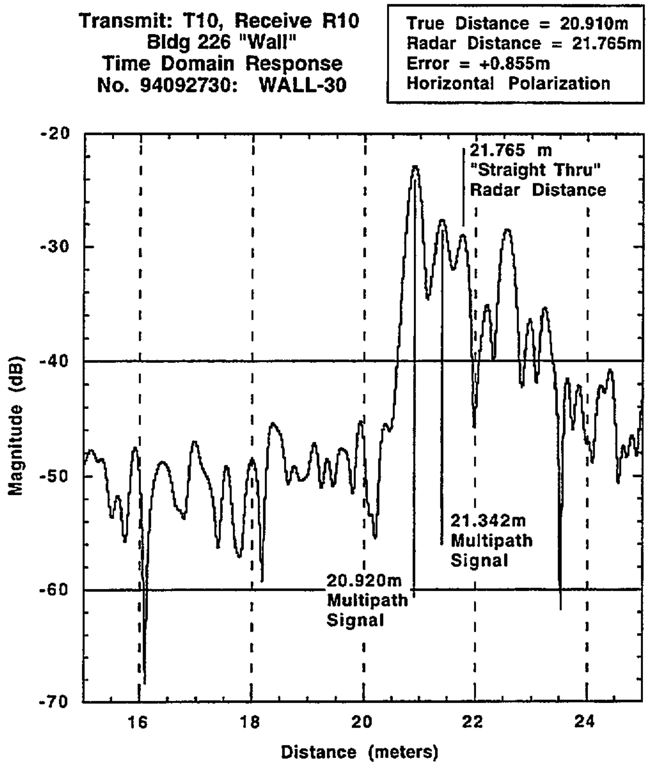
Above: Time domain response for a spread spectrum radar signal propagating through air. The exact distance between the electrical centers of the two antennas was 14.905m. Such data was used to periodically calibrate atmospheric conditions.

However, the presence of even small openings (on the order of several centimeters) permitted range acquisition.

Several types of problems which are well known to the radar community were observed during the tests. These included "clutter" (reflections of the transmitted beam off false "targets") and "multipath" (diffracted and scattered elements of the original signal which may, under certain conditions, arrive ahead of the



desired signal and which as a matter of course may obscure or cast doubt upon which detected signal in the time domain response represents the true transmitter-to-target distance). Another phenomena that was observed is well known to the optics industry: electromagnetic radiation which propagates through a medium other than a vacuum travels through that medium with a velocity less than the speed of light in a vacuum. Thus, any signal transmitted through a non-conducting engineering material -- e.g. brick, masonry block, or concrete walls -- will appear to have been delayed from its expected arrival time at the receiver. In some cases this delay was sufficient that multipath signals arrived ahead of the "true" signal representing the straight-line distance from transmitter to receiver. The delay is directly proportional to the dielectric constant of the engineering material penetrated. Where long dis-



Above: Time domain response for transmission from benchmark T10 to Station R10 (actual point-to-point distance = 20.910 m) at the NIST Building 226 NLS test range. The 500 mm reinforced concrete wall is between the transmitter and receiver. In this particular situation the propagation delay times associated with diffracted and reflected multipath signals are sufficiently separated that the individual peaks are clearly identified. Note that the straight "through-the-wall" response peak is the **third** detected, behind the two principal multipath signals. The first peak was diffracted around the interior corner at the junction of the two wall slabs; the second peak represents the signal reflected from office trailers to the left of the wall.

tances are involved between the transmitter and receiver, the characteristics of the air (including temperature, humidity, and barometric pressure) must be accounted for as well; during the NIST tests this was accomplished by means of a "free space" calibration with no intervening obstacles between the transmitter and receiver at the start of each test series.

Typical errors observed due to uncompensated propagation delays were significant. Penetration of a 500 mm thick reinforced concrete wall induced a range error mean of approximately 800 mm. For combined masonry block walls faced with brick, range errors of three meters were observed for a wall thickness of two meters and a 500 mm error for a wall thickness of 300 mm. Plots made with the limited data available indicate that these range errors are linearly proportional to the penetration depth (wall thickness) and the dielectric constant for the material.

While 800 mm of range error over a 20 m survey shot is unacceptable for modern construction surveying, it is important to recognize that nearly all of the error is related to propagation delay in concrete. This suggests that real-time compensation techniques can be developed which will be capable of eliminating this portion of the error. We are presently investigating the idea of constructing a three dimensional database for the project which reflects the as-built geometry in real-time and which includes propagation characteristics and statistical variances for the various materials and then employs a ray tracing approach (borrowed from computer graphics technology) to follow each transmitted signal. A discrimination algorithm will need to be developed which will then, based on statistical analysis of the multiple time histories generated via alternate transmission stations, determine which is the true target and to calculate its location and expected SEP (spherical error probable). Data developed as a result of analyzing Building 202 tests suggest that the residual errors that will remain after propagation delays are compensated will be on the order of 200 mm or less. It is anticipated that this number can be substantially reduced through a) the use of larger bandwidths in the transmitted signal and b) the use of super resolution (image enhancement) algorithms which will improve the signal to noise ratio in the received signal.

We think these results are both novel and encouraging. Confirmed distances (target detection) were obtained through a 500 mm thick reinforced concrete wall and through nearly two meters of brick and masonry block. The transmission power for all tests was only 1 milliwatt. During the next year we will be conducting tests to determine the statistical transmission characteristics of most construction materials.

1.6 Data Exchange Standards for Construction Automation

Kent Reed
Building and Fire Research Laboratory, NIST

My computer integrated construction group was created some ten years ago to address data exchange standards and other issues related to helping the construction industry apply computing and, in particular, to help the construction industry integrate its use of computers.

Most of the work that our group has done in the past has been related to what happens in the AE offices, what happens with regulatory authorities, what happens in manufacturing and fabrication. Introducing the construction site adds new features that we have not addressed directly although we've always said we're dealing with the product life cycle which would include construction and include operation. Most of the work, to date, has been in the fun end of characterization of the construction project. The problem is that we deal with a lot of data streams. Lets let this one computer be the exemplar for all the computers in the AE office, some in the construction shack, some on automated equipment. So there are a variety of data streams. How do you integrate this system so that you get beyond having one computer for each task and human beings laboriously translating between computers or inferring the meaning of the data? It happens that work that's been going on in the past has addressed project design data; it has addressed vendor product data, but not most of the other streams which we're talking about here: for example, getting static site data from GIS systems into this manage. Getting real time site data from the kinds of measurement equipment Bill was talking about and Eric talked about, control data back out; those are new features we have to address as part of this initiative.

Being a loyal member of the National Institute of Standards and Technology, of course I think standards are the way to pull this off. In fact, there are strong arguments for consensus standards being the way to integrating information technology systems — and I won't go through all of the arguments for them now.

Certainly one particular objective is, you'd like to get the information out of the application software. Systems in the past tend to integrate by pushing lots of applications together through custom interfaces and your data had meaning only in the context of those applications. We're trying to develop neutral data exchange standards where the data can be captured and can be reused and can be understood outside the context of the specific application. Something we have to address very carefully in this initiative is how do we handle the incremental introduction of automation. Clearly we're not going to satisfactorily integrate everything on the site all at once, it just isn't going to happen. So standards which require that, aren't going to make it to the marketplace, in my opinion.

The kinds of trends we see in information technology standards are both good news/ bad news kinds of stories. First of all, in the last ten years, data exchange standards have moved more toward semantics-based exchange rather than simple data structures. The good news is it makes it easy to understand the information streams that you have without the resource applications that generated it. The bad news is that you have to participate in the definition because its your semantics you're trying to capture. It's not something that some computer jock back in the software house is likely to be able to do by his or herself.

Another trend is pluralism, we have recognized that there's no such thing as the one-size-fits-all standard. The fact that in information technology more and more we see many different standards emerging and being carbonized. The good news is, you kind of get to mix and match standards that fit your problem. The bad news is that carbonization takes a lot of work. You actually see that technology changes faster, accounting for the harmonization of standards slowing down. We're trying to figure out ways to improve on that set when in fact other parts of NIST are directly addressing how to speed up the creation of new standards.

Another trend that I find very helpful is that all of these standards are moving towards open systems environments. I'll try not to define open systems very carefully, but in effect that it allows them to plug and play with different application software packages, more-or-less without recourse to the harbor platform. Often without recourse to the operating system as well. Those trends are very good news for us in the construction industry, precisely because we are such a dispersed group of actors. We deal with descriptive and heterogeneous systems and that's just not going to change.

A quote that you often see floating around the standards community is, "the wonderful thing about standards is there are so many of them." That is particularly true in information technology in core streams, ranging from almost proprietary standards to the best and most widely distributed national standards. We've got this alphabet soup of standards -- all of which may apply in some way to our problem -- from the drawing exchange format for AutoCAD, Microsoft's Object Linking Embedding environment (which is still kind of a now you see it now you don't standard), RSA which is the leading industrial method for encrypting and authenticating data etc. Industry standards that have not been developed by single vendors are in some sense more accessible. National standards are generally maintained by consensus standard bodies in the U.S. IGES, or ANSI interchange format, are examples of such standards. And the various international standards. The trick is to figure out where to position yourself along all this mess as we deal with particular parts of the problem. I'd like to talk about just one of those. Bill's put me into a session called "State-of-the-Art". I won't quibble about that. Sort of generically the NIST approach in all these standards is : "let's try to work with industry to find out what the requirements really are for a standard and help develop technical solutions that meet those requirements." Typically, we develop within NIST experimental standards and/or reference implementations that help best reach the solution. We work with the appropriate standard bodies to produce the resulting standards.

One of the features of NIST is its continuity. It has staying power in activities that would cause people's eyes to glaze over. Most company's say we really cannot afford to keep going back to more meetings. But in effect, by working through this, we can be an effective voice for industry within the standards body, and then try to close the loop working with industry to implement those standards. To make sure they actually work, provide interoperability. That's kind of a general mesh that lays over a lot of our work, whether it's my group or groups in other laboratories.

The specific standard I want to talk about, because I think it plays a key role in this initiative, is informally known as STEP — Standard for the Exchange of Product Model data. It's an ISO standard, and it's one in which there is considerable U.S. effort, in fact, probably more than 50% of the labor has come from the U.S., including a lot from NIST. It is just now starting to emerge. The first parts were approved as an international standard this last year. Fifteen industrialized countries voted to endorse it, including the U.S. And NIST worked with other technology based organizations to develop the core concepts.

My group has spent a good deal of time working with U.S. industry to try to understand what the AEC requirements, from the perspective of the construction industry, are with respective to this stuff. I'd like to say that all parts of the construction industry have been equally represented, but it is really not true. Most of the responses we've gotten have been from the ship building industry, which thinks of itself as kind of an AEC industry. They also deal with large scale, one-of-a-kind projects. I often talk of the ship as being a building that broke away from its mooring. Maybe I should talk about buildings as ships that ran the pier. But we have had substantial interaction with the ship builders over the last five years to define these solutions that deal with piping systems and ship structures and so forth. We've had considerable luck in the last few years dealing with what we call the process plant industry — owners and operators, engineering and construction companies, fabricators, and suppliers and vendors. We are trying to define what STEP has to do in the near term to satisfy their requirements. We've been working with the international community to develop technical solutions that meet those requirements.

Let me say a word about how we have been working with industry, particularly with the process plant industry. We have been successful with getting U.S. industry to create a consortium, called Plant-STEP, Inc., for processing industries. It includes plant owners and operators, includes engineering and construction companies, suppliers and IT vendors. We are formally related to this organization through a CRDA, which lays out what we bring to the table. It's really a response to work that's already going on in Europe. In particular, in the United Kingdom there has been a strong effort over the last few years to develop interesting stuff from the process industry perspective. Through European union funding and the ESPRIT program, the European Special Projects for Research and Information Technology that has been working with databases that support process plant engineering, and some other activities including one that is rather substantial in the Netherlands.

Japan has recently come on line with two efforts, which have been very supportive of the U.S. efforts by the way. It is surprising that the Japanese and the U.S. efforts are more in alignment and both of us seem to be somewhat in conflict with the Europeans... a rather different state of affairs than we've seen in the past. There are some other activities in the U.S. — there is the process data exchange institute from the American Institute of Chemical Engineers. It's possible that the Petrotechnical Implement Software Corporation will participate in STEP, although we are still working that out.

Well. Why should we care? Those activities European, Japanese, and the U.S., have collectively tried to carve up the universe into the life cycles of a process plant. There's has been an activity model that has been defined and agreed to internationally, and I have grossly simplified that activity model. Its really not intended to deal only with new construction, but you might assume that for the idea of starting with process design. That might just as well be, you have a model of an existing plant, what do you do to re-engineer it to bring on a new specialty chemical stream, or what do you do to introduce a new power cycle?

Process Data Exchange Institute is focusing on parts of the process engineering work. The European activities have tended to focus on information that would back up the creation of what we can a P&ID process and instrumentation diagram. The U.S. activity is focused more or less on the 3D modeling and associative attribute data.

To break out a little bit about what Plant STEP is concerned about, it has grossly divided up its world of information across different systems like piping systems, and process equipment, structural systems and so forth, and has done a gross break out of the types of data that are associated with each of those. Product ID goes across the board. The same questions as were shown in Bill's slides concerning product ID of an object on the site, we now are dealing with it in the design phase.

The issue then, from my perspective, is, assuming that STEP is the primary data exchange standard for describing the project as designed, and the primary standard for describing products as required, that is fabricated parts — steel members etc. — what else needs to be done? Well certainly, STEP needs to have as part of this initiative either bits filled in or additions added on to it that deal with more construction phase information than is presently shown. There are other systems for which there is no provision for this type of data, and even in the case of piping systems, which has the most details, there is precious little there in terms of how would you sequence the installation of a piping system. For example, how would you take a large reactor vessel and drop it in place? What is the rigging involved in doing that? What kinds of cranes are required?

There is a companion standard, ISO 13584 Parts library, which needs to be applied to the construction products business. This is not nearly as far along as STEP itself, but in principle in the future your steel fabricator will supply all his catalog data in the format of this particular standard. But we don't know for sure it really works with construction products.

Bill's already alluded to the notion of models of construction equipment and construction equipment operations. We do not yet have a framework established for that, nor for the kinds of models we have been discussing. It is conceivable that the data for these would be exchanged using STEP, but it is just as conceivable — because software technology is a moving target — that by the time we want to standardize on this. It's conceivable that we'll use STEP for defining the static parts of that and maybe using something like the system object model from IBM as the way of defining the methods. There is a good deal of work yet to be done experimentally to see what really works and what doesn't really work in a construction-related scenario. And that may mean identifying and incorporating other standards that we may need.

Clearly, something that has to be answered fairly soon in our program is: what do we do first. We can't possibly model the whole world. What things do we need to focus on, first. That is why we are looking to close interaction with industry to help calibrate what we are doing.

Questions:

Chuck Schaidle, Caterpillar: *What do you see happening with standards for the earthwork design of the site? Topography modeling etc. Do you see STEP getting into that?*

Kent Reed, NIST: In the Plant STEP defined model, there is a primitive terrain model element. It basically says there is a collection of xyz data. And from that, many things could be derived within a particular system. But that is about as far as it has been elaborated. There is no sense in that model yet as to whether this is the undisturbed site or is that after the first cut, after the second cut, as the site is manipulated to create the plant. Even in that model, there needs to be more thought given to how to categorize the data.

Chuck Schaidle, Caterpillar: *Is there anything outside of STEP that is further along in setting standards for digital terrain?*

Kent Reed, NIST: I haven't kept up with that. There was a time when I was the chair of the AEC committee when I tried to stay tuned to the digital terrain folks, the digital cartographic folks and some other activities. My sense is that there is a lot of competition as to who thinks what best approach ought to be taken. It really hasn't been tested on an open forum to my knowledge. I don't think its an insoluble problem. Right now we are being offered this cacophony of solutions.

Bob King, CSM: *Does STEP incorporate a standard format for transferring surface information on 3D solids?*

Kent Reed, NIST: In the interest of both compressing time and not glazing your eyes over, yes. STEP has incorporated in it some key base models including a variety of geometry models, topology, configuration management, but the way STEP is constructed you never exchange those things raw. What you exchange is an interpretation of the model in its context. It has a fully surfaced geometry model available, but you would first define what your requirements are for that, what is it you are going to send as a surface model? That's simply one representation of data about something. It may be terrain, it may be the exterior of your vessel, might be something else entirely, but unlike IGES, DXF, and the standards of the last decade you will never be in the situation with STEP where you are simply going to send some geometry and the receiving system tries to figure out what is the meaning of that geometry. That was defined before you sent it.

Chuck Schaidle, Caterpillar: *Are any of the software manufacturers that do 3D solids, kinematic modeling that we have been talking about, like Symmetrics, Deneb, any of those people, are they working with this group?*

Kent Reed, NIST: I'm not really competent to say who's solidly involved that knows a lot about kinematic modeling. There is a kinematics interest group that has not been very active recently. The CAD vendors that represent the bulk of the process industry, for 90% of all the CAD seats being used to design plants, those were represented at the table. But again this issue coming into the construction site, dealing with dynamic as well as static data is one we have to address here. Even if there is kinematic work going on at STEP, the likelihood is that at best it addresses the needs of the piece part manufacturers and part assembly drawings, not really the construction site.

John Schlecht, Iron Working Institute: *It seems to me that this maximum re-use of information, that we are almost there in some parts. Like you said, where to start? If you think of a steel building, at the time it is being designed if we had the data input that would give the fabricators that are bidding on that job they could all use data that would tell them the number of pieces, the way to connect them. So lets say 10 fabricators are bidding on the job, you wouldn't have 10 people doing the same thing, taking it off to bid. OK. So there you would be re-using that information when you do a take off from it. Then the fabricator that gets the job, the winner, the low bidder, the next thing he does, he has somebody sit down who clerically has a bill of materials, and he orders it from the mill. That would be an overlap. The information in the design could be used in the fabricating shop for cutting, drilling, and punching, and for the size of the members., for which the standard is the rolling mill. And the next step would be that that data would also provide the erection drawing or placing directions. So if you visualize a logic path, it seems to me that if the data is input in the design phase it should be able to be re-used over and over again, almost to the point where the remaining thing would be the 3D — to see in real time, where is the member being set compared to the erection plan, in* *real time in 3D. So, it seems to me we can do this, and there would be a tremendous enhancement for cost in construction.*

Kent Reed, NIST: I agree with you 100%. I think the construction industry is a little bit behind. In the case of the ship builders that is precisely the scenario they have thrown up as the reason for developing the STEP application protocol. So the Navy can pass a preliminary design through a design yard, a design yard can detail that, pass it to a construction yard, and the construction yard build a ship of that class and pass the as-built data on to the logistics guys who support the ships in the fleet. That is precisely their point of view.

***Bob McClelland, Fluor-Daniel** Seems to me that that technology is already available in the form of the PDS. If you take a PDS model and transmit that to the vendors, they can use the tabular data within PDS to take off any sort of information.*

Kent Reed, NIST: And is it available in several different third party vendors that build on top of AutoCAD, and its available... I can name a number of CAD systems, but try to take it out of the PDS system and put it into the third party vendor software from AutoCAD. Or vice versa. You start getting into troubles.

***Bob McClelland, Fluor-Daniel:** It means that everyone's got to use a system that is compatible with each other.*

Kent Reed, NIST: And the point of trying to develop a standard like STEP is to reduce the number of times when you have to use the same system as your partner. Or at least a fully compatible system. If you cannot do it directly, then you cannot do it through a standard either. That is one of the principles that the standards writers sometimes forget. You can't create a solution that can't be done technically. If they can, then standardize the solution so that it is more accessible.

1.7 Global System Architectures for Construction Automation

Ernie Kent
Manufacturing Engineering Laboratory, NIST

Much of what I would usually talk about in this presentation has already been given, either by the presenters or by some of you and some of the questions that you've asked. We, some years ago, saw coming many of things that you've been hearing about today in terms of:

- Capabilities for measurement and data collection on the site in real-time
- Capabilities for presentation of information in real time, to people working on the site
- Integration of data bases of a wide variety

We have been working for some years in the Manufacturing Engineering Laboratory in the area of automated control for manufacturing, real time control systems, called RCS.

It seemed to us that the opportunity was emerging for possibly bringing into the construction industry some of the kinds of technologies that have been developed, are being developed in the manufacturing industry. Now, in the manufacturing industry of course you have a much more constrained environment which makes life a lot easier. It's much easier to place sensors, it is much easier to know where things are, it's much easier to predict what is going to happen. Looking forward to the advancements in technology that we expect, we foresee it may be possible to bring some of these characteristics to construction sites.

So, the over arching notion, here is one of complete life cycle management. If you think about manufacturing industry, you have such things as CAD designed parts, process plans, you'll also have real-time control of what is going on, you'll have control of machines and robots from both those data bases that have to do with planning and scheduling of operations and from real-time measurement of what's actually happening, where the parts are and what the machine is doing.

Those things result in real time control signals that are given to machines or to people. You can have a man in the loop just as easily, and in addition you can actually measure what's happening and you can collect new data bases. You can get the equivalent of the as-built data bases. Basically, as the point was raised, this comes for free because you're taking the measurements in any case or to control what's going on. So, we asked what could be done, in the future to bring this type of paradigm to a construction project.

Now if you think about the best way to consider a real-time control systems for a factory, think about the hierarchical organization of the factory. At the top you have a manager, under him you have a sub-managers, a production manager, you have someone in charge in accounting, you have an inventory manager, under these people are people with more specialized functions. Then you get down to the machine operator on the shop floor who is under the control of perhaps a supervisor that is controlling a production cell. At the top you have the global level you have planning over a long time scale you have fairly general commands given to the people lower down. As you go down the hierarchy the planning horizon shortens, the commands become more specific, more specific kinds of data are required, and more specific instructions are given. And in a real time control system basically you could consider every one of these levels to represented by some piece of software, accessing the appropriate information, the plans, collecting information on what is going on now, according to some state tables or rules generating the next command that's given to the level below it and this flows down through the system. Status reports ripple back up, which may include, "I can't do it because something is broken," in which case a new command is sent down to do something else or utilize a different piece of machinery.

Now, in manufacturing applications, it is possible today to do this in a completely automated fashion. Typically it is not done everywhere. Typically you get portions of automation like that or automation may extend down to a certain level or you have man in the loop at various points where the device receiving the instructions is actually a human being who carries it out and then reports whether he's done it or not. But, within the constrained environment of manufacturing, capabilities exist to do this today. We have been working on RCS for about a decade and a half now, so we have a great deal of expertise in that area.

Of course we don't have a great deal of expertise in construction and we have been working with people who know something about it. We've been working with people who know something about automated scheduling and planning up at Rensselaer Polytechnic. We've been working with Kent Reed who knows something about construction data bases and how to interface them. And we also are working with Advanced Technology Research, ATR who is bringing together some of the technology that has been developed at NIST and applying it to real automation facilities with great success.

So, we proposed to the Federal Highway Administration two years ago, that we undertake a project in site integration. This was funded and managed by Charlie Woo and has gone forward. We now have looked at construction from the standpoint of highways and we're now hoping to work with BFRL in the future to continue this investigation in building construction.

I'll tell you a little bit today about what we have accomplished so far, what we've been doing. I won't go too much into the sensors, into the displays, those have been covered in the last few speakers and the data bases. Kent just gave you a good summary of the state of the art there. But you'll notice that in all of those there is the assumption that artificial intelligence somewhere is going to collect the information and make it useful or decide what is to be presented in the display or to give to the man on the site. That is really the area that we want to talk about, what happens there. The goal is for the complete life cycle management, we want to be able to leverage on the construction site, all of the data that's generated during the design. Typically you get CAD data generated, you can get access to it but it does not interact with data that you are collecting at the moment to produce some sort of decision process. To enable you to reschedule in real time, to ask "what if" questions. Another advantage is to ensure consistency between the data from multiple sources, do these things really match up to be able to give you a look at them, to walk around in it, a virtual reality presentation to see inconsistencies to have matched up with the requirements data bases.

Obviously, this reduces the cost of man hours in the interpretation of the data and provides integrated access to information from multiple formats and multiple sources. We want to bring all of these things into one world model that brings together the real-time information, the planning information, the design information, and integrate that to enable us to generate real time looks at what is going on.

For constructability, basically this is what we said, we're going to apply computer technologies to optimize the use of construction knowledge. Part of this involves going out and doing what the artificial intelligence people call knowledge engineering. You have to go and find out what people really do on a construction site, what they really know, and somehow squeeze it out of them and put it into a rule base that our artificial intelligence system can use. We're not talking about replacing the engineer. You're never really going to get away from the real world knowledge that this guy has generated over the course of a life time. What you want to do is to be able to leverage his knowledge by being able to present to him in a unified way a lot of information quickly and present to him alternatives to perhaps to call to his attention the consequences of decisions that he may make. To let him say I want to do this, and have the system say to him, "Well, if you do that, then this is going to be delayed, and that is going to be there, and its going to be in the way of this, do you really want to do that?" Then have him say, "Oh well, yes, you're right," and correct his decision.

But basically this gives him the opportunity to say, "yes, I know more than you do about it and that's exactly what I want to do." We think it will have a big impact on safety because as has been mentioned we can monitor in real time the movement of equipment, the location of workers, and the computer isn't going to overlook something. It isn't going to forget that there is a man behind that hill when you push the dirt over it. It is going to tell the operator, "Hey, stop Don't go that way!" because it is going to know which way the bulldozer is heading and it's going to know where the man is. There is, also the requirement to place retainers and safety shields to make sure that hazards are not overlooked, not letting anybody into a hazardous environment until all requirements have been met etc..

So the concepts are to coordinate and interface all of these different construction databases including data bases that will have to come in the future. Not all of these exist right now. Right now we've got a problem with, for example databases with pre-existing obstacles. We've got buried pipes and things and probably they're written down on paper somewhere in the basement of city hall and nobody knows where they are and nobody can get at them. Over time, as we are collecting real-time information about where these things are put as they are being put down, those data bases become available to future projects. Over time, we evolve towards a system in which they are available in real time on the construction site.

We want to look at scheduling and planning. Right now scheduling is typically done once before you build it. You have it to work with. You have that schedule to try to keep to, and you always get off of it. That schedule goes bad after a very short time, and people are always hopping trying to catch up with it. There is no reason that we couldn't have scheduling and planning done in real-time, taking in to account things that happen, i.e. a piece of machinery breaks, it rains the night before, the scheduler says you're going to be delayed by this much, this machinery is going to be idle; why don't you use it over here instead. Or the forecast is for rain so you're going to need a pump here tomorrow morning; let's order it now. There is no reason why that kind of revision of scheduling and planning even down a fairly microscopic level can't be done in real time to make use of men and machines more efficiently.

The benefits can help the designers visualize all phases of the project. This can be done today, you know the Boston tunnel project virtual reality simulations — you can walk through it and see what it's going to look like. We'd like to be able to do that at all phases of the project in real time. We would like to be able to say, "OK, I want to make this change because that happened, and I've got to do this a little differently and what is it going to look like?" Then walk in and see it and have it light up in red and say these are going to be here tomorrow and by the way this isn't going to be here and you're going to need it. It enables managers at the higher level to interact with the design planning and scheduling process in a highly graphical format that helps them really integrate in the best possible way a large amount of data. Optimize location of materials and resources, site planning, planning to bring in real-time scheduling and manage and monitor all the on site activities in real-time, providing advice to supervisors of potential events.

These are the kinds of things that can be done in manufacturing today and which we hope are going to be done in construction in the future. These are the things that we have been working on. These are the pieces that we need to bring together. Some of these you've seen already today about sensing and site positioning, network communications, data bases, advanced visualization techniques. Really these are the two key items: real time planning/scheduling assistance and intelligent information control that are the core of the site integration that we're trying to bring together.

We've been working through knowledge acquisition, development of knowledge, and databases. Characterizing a work-site, we were initially going to work with FHWA to build a bridge. That actually didn't come to pass, and as you see we've fallen back to a somewhat more modest experiment. Schedule and planning is being done up at Rensselaer Polytechnic, hierarchical control work is being done at ATR and here at NIST. Simulation is being done at ATR. Bring these things together and we have a virtual construction installation which mirrors the prototype construction site. And in real-time operation then there would be a real time control system that would have this available to it as well as input in real time from sensors, which would generate commands in real time and can do it at all levels of the hierarchy of control on the site.

Bringing together three kinds of databases: spatial data layers that are geometric information, geographic information on the site, construction data layers and the document data layers. I'll say a little bit about what's entailed in each of those. The spatial data layers involve your ground controlled topography, terrain modeling, hydrology, soil conditions etc. There are any number of things that can be brought in here. Obviously a great many of these do not exist today in computer accessible formats. What we're trying to do really at this point is more to identify the kind of things that we're going to need and to begin the work towards the development of data bases that will satisfy those needs and of course standard ways of interfacing them and bringing them into the system.

Construction data layers would include all of the things that you need to know about to build something -- including some very nebulous things like construction method. This is the kind of thing that knowledge engineering has had to address in artificial intelligence in construction of experts systems, which have reached some degree of acceptance in manufacturing now. But it certainly needs to be developed for the construction industry. We have been in a small pilot project attempting to do some of that. The document data layers of course include the contracts, systems drawings, reference manuals, directives and so on, that have to be (in many cases) actually compared with what is sensed and measured or what is in the plans. Kent has already talked about the need for data standards and interfaces. Other people have talked about file sharing connectivity and so on, we don't need to belabor that point -- it's obviously a big road block.

What we're doing is looking at a very simple thing that involves a number of different kinds of activities in the construction nature -- a storm sewer installation that was of interest to the Federal Highway Administration. These are the phases of the tasks that we have been modeling. Basically all the operations that are required to put this thing into place. We have developed a terrain model that is fully interactive, including soil stratification, interfaces to some existing data standards and databases.

We've developed a drive-through capability in real time. You can drive through the site, see it from many positions, see it from the position of the supervisor, the back hole operator, see if from anyway you like. We can do cut and fill and cut through soil stratification to show you what it would look like at any point in the excavation, backwards and forwards in real time with regard to trenching and pipe laying, for example. I'll give you a look at what this shows. This is the terrain model, the colors indicate different kinds of terrain: top soil, clay, water, bedrock. In real time you can move around and view this from any position and you can zoom in, fly out, and so on. The soil stratigraphy is maintained in separate data layers so that if you cut down you can see what is going to happen.

Here we have an overview at some point a little further along in construction. This is section highway here. We're doing some traffic modeling as well. Here is the pipe being laid, you can see the trench that has been cut and you can see the bedrock is getting exposed. This is a piece of equipment here. Down here you see the view of this scene as seen through the window of this system and you can drive this machine around in real time and you can have these two views of it. The supervisor can watch the machine moving around in here and he can zoom himself down and look at it from any angle and at the same time the operator can see this. This can be an overlay presented to a heads-up display on the operator. We can put various kinds of information on this and it's fairly impressive in real time as you drive around.

Now, this is just another example of A different view. This is the enlarged view of what the equipment operator sees in the planning phase. We can use these buttons to actually drive a simulated machine around the simulated drain before we ever actually get to the construction site.

Now, here is where we begin to get into some of the interesting kinds of applications. This shows you what happens after a rainfall. Here is our trench, we know basically what the amount of water is that has fallen. And we are able to now tell you that at this time, this is going to be the water table and what the outline of it is going to look like. In fact if we know something about the predicted rainfall, we can probably tell you what this is going to look like by noon. Now, what can we do with that kind of information? We can bring in another kind of database. Here we have installed a pump and because we are assuming that we are somewhere in the future and are able to bring in on line automatically and interface to the information from the pump manufacturer that tells us what this piece of equipment can do, what its pumping rate is and so on. We can tell you what the water table is going to look like and what is going to be exposed and whats not going to be exposed after so many hours of pumping at such and such a time in the future. So this would enable the supervisor the night before to say, "OK, you've accessed the weather bureau's data base; you know what their predicted rain fall is; you have accessed the pump manufacturer's data base. If I turn it on at 6 o'clock, what are things going to look like tomorrow at noon. Will I be able to work in this position or not?" And he will be able to get this kind of display.

Obviously we're a long way from that but, we are not a long way from that because we don't have the technology to do it. We are a long way from that simply because we do not yet have the standards to integrate the data bases, we're a long way from that because these data bases have not been put on line but that is all work that can be done. The message that I want to bring you today is the real power that we can get from a concept like site integration if we go ahead and do the work to do those things. The technology exists today to do it. Of course in the process we're getting real time readings on all of the sensors and we're actually constructing our as-built data base for free. Thank You.

Open Discussion

Chuck Schaidle, Caterpillar:What kind of a computer system processor and storage do you need to display that?

Ernie Kent, NIST: This is running on an Onyx ... that's a big expensive machine. Our concept is that at the level of the supervisor on the site, you probably got one of these little hand held boxes like a federal express delivery man has and he can punch in information that says "tractor #9 is broken, what should I do?" and maybe he just gets some little printed display that says, "do this instead, or wait 10 minutes and I'll dispatch a truck."

Bob McClelland, Fluor Daniel: How well would that work on a TD 4 or TD 5, 90 megahertz dual pentium computer?

Ernie Kent, NIST: Again, I think it depends on the supervisory level that you're talking about. I would say that for the equipment operator, for the supervisor, that works pretty well. If you are talking about somebody back at headquarters which is concerned about planning things out six months down the road and walking through a virtual reality display and say, "well, now its July, what's in place and what isn't and what do we have to worry about in terms of materials delivery?," then you're talking about a lot more horsepower.

Bob McClelland, Fluor Daniel: For instance on a jobsite we might have a server that's based on a TD4 or TD5...

Ernie Kent, NIST: You can talk about that kind of power on the jobsite. You can talk about virtual reality displays back at headquarters. And of course, links between the two. Real time at that level does not need to be all that fast. We're talking as fast as you need it, which can no doubt be on the order of minutes.

Bob McClelland, Fluor Daniel: The technology exists right now to hook a fast computer to a notebook computer via a spread spectrum RF signal. The only problem is moving the graphics files.

Ernie Kent, NIST: On a piece of equipment, where you are going to do a heads up display, you are going to do graphics overlays, you are probably going to need some processing power. But I think its already been brought up that you are talking about a very expensive piece of equipment here and even that much processing power doesnt add that much proportionally to the cost of the equipment. A lot of people don't need graphics input. You can do with text based input that simply says, now do this, or now send that crew there. Don't lay that there because there's a truck coming by in five minutes.

Bob McClelland, Fluor Daniel: *Did you base this on some existing software package from a vendor or did you write the whole thing from scratch?*

Ernie Kent, NIST: This was based on software that has been developed by ATR for their use in some automation of postal mail facilities and other things.
Bob McClelland, Fluor Daniel: *so it was similar to what was used for developing the RCS?*

Ernie Kent, NIST: Yes. There is nothing in this that is extremely high technology or out on the forefront. What we are talking about here is taking capabilities that pretty much exist today and putting them under a system that monitors and controls them and integrates them. The real thing that doesn't exist today is getting the data bases into computer readable format and interfacing them. Then we can do it all.

Bob King, CSM: *Do you actually do digging in this software, where you can move that little front end loader and take a bite of dirt and then you see exactly what is left?*

Ernie Kent, NIST: Yes. Of course you have to be able to model that. You have to model the capabilities of the machine. You have to have a physical model of what the bucket is going to do. But those kinds of things really only have to be developed once and they can be developed by the manufacturer of the equipment and provided in standard format on a disk.

Bob King, CSM: *But there are no standard formats?*

Ernie Kent, NIST: Ernie Kent, NIST: No, there are no standard formats.

Jim Albus, NIST: *For example, if you develop a kinematic model of that excavator here and I want to import it into one of the standard kinematic modelling software packages like SimStation or IGRIP, I can't do it.*

Ernie Kent, NIST: That's right. Today, those standards do not exist. And that's one of the reason that NIST is particularly interested in this kind of thing, because it really is a standards issue.

Bob King, CSM: *Did you model the materials that are moving here, the water and the soil, did you model those as small cubes so that when you take a bite you are moving a certain number of those very small cubes of dirt?*

Ernie Kent, NIST: I would have to talk to the programmer on that, I can't answer that off the top of my head.

Bob King, CSM: *That's really the essence of your question. As you begin — it's not difficult to model an excavator with a kinematic model and so forth — it dosn't take a tremendous amount of space. But when you have a large site, and that large site gets modelled as very small elements, discrete elements, each one of those elements becomes a file in itself and all of a sudden you get extremely large databases, especially if we talk about moving each one of those files.*

Ernie Kent, NIST: Are you storing voxels or are you generating surface models...

Jim Albus, NIST: But that sort of a deal where you have to move all the water on the site, or you have to move all the dirt and the rock on the site... that type of system is not capable ... you'll fill up the Onyx pretty fast. You certainly cannot do it like that.

Ernie Kent, NIST: You'd have to do things like, from geometric considerations, compute the water table and find its outline and then fill it in for a visual presentation from some angle.

Bob King, CSM: *That's all just a video game or a model, that doesn't even incorporate any of the real data coming in ... it would be hundreds of millions of dollars to get that. You say the technology exists today. If the technology exists today, is this then the right arena for NIST to be working in? How do you share the research and the development responsibilities, where is the high risk item here that is appropriate for NIST?*

Ernie Kent, NIST: I think really it is very much in the line of NIST's fundamental mission for standards because all of these different software packages, all the databases for that matter, are potentially commercial items that people will be designing, producing, and selling. There will be a big market for databases for this kind of stuff. There will be a big market for different kinds of planners and schedulers or display systems and so on. There is developing a big market for real time control systems but the issue is that those markets cannot develop now because of this issue of interface standards. If there is no standard format for tying these things together. We see that as NIST's mission to try and remove that roadblock to enable really a whole industry to develop here that will be a supply industry to the construction industry.

1.8 Summary of the ARPA Head-Mounted Display Programs

Henry Girolamo and Ron Lewandowski
U.S. Army Natick RD&E center, and Honeywell Corp.

The Need for New Display Technologies

The limitations of CRT-based HMDs, and the need for technological improvements have been voiced by subject matter experts in the HMD domain over the past several years at display conferences (i.e. SPIE, SID and others). Current CRT-based HMD limitations include expense, weight, and high voltage requirements which prevent them from being used in certain systems such as lightweight systems that could be worn on an individual's head. Next-Generation flat-panel display technologies, optical designs, and packaging techniques are essential if HMD systems are expected to be utilized as situational awareness and performance enhancement systems.

Tactical Military Requirement

In 1988, the requirement to have a head-mounted, integrated battlefield communication and information management system was set forth by the U.S. Army Training and Doctrine Command (TRADOC) Fort Monroe, VA in the Battlefield Development Plan. The U.S. Army Research, Development, and Engineering Center (NATICK) began a study to research the feasibility of such a system. When this study began, it was a next-generation future-system feasibility study. Technologies that could be physically or potentially capable of multipurpose and modular integration were explored and evaluated for application in tactical military systems.

The resulting notional integrated head-mounted system would enhance performance in target recognition, weapon sighting, fire control and reconnaissance missions. The HMD would have a multi-purpose full face shield that would protect against ballistic hazards and directed energy weapons (e.g. laser). The display would include night vision enhancement capabilities, electro-optical weapon sights for remote weapon sighting, display sensors that warn of atmospheric threats (e.g. radiation, chemical/biological agents) and display sensors that monitor the soldier's physiological condition.

A CRT-based system, the Soldier Integrated Protective Ensemble (SIPE) demonstrated by the Army at Fort Benning in 1992, was the beginning of a systematic approach to utilizing miniaturized electronics

Advanced Flat Panel HMD

- **Full color systems -- spatial and sequential**
- **1280 x 1024 x 6 bits/color AMEL and AMLCD image sources**
- **24 μm and 12 μm formats**
- **3 Volt low- power electronics**
- **Standard bus interfaces for electronics**
- **Army medical application**
- **2560 x 2048 system support and static HMD demonstration**
- **ARPA funded, US ARMY contract**

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to enhance command, control, communication, lethality and survivability in a battlefield environment. The fielding of a power-hungry, heavy, and bulky CRT-based HMD system was considered a logistic impossibility. New display technologies were essential if head-mounted displays were ever going to be man-portable systems.

ARPA - High Definition Systems Program

In 1991, The Defense Advanced Research Projects Agency (now known as ARPA) published a High Definition Systems Broad Agency Announcement (BAA) requesting proposals from companies with innovative display technologies. ARPA's goal was to develop (with industry), inexpensive, high resolution displays to replace the current CRTs used in almost all display systems. The new displays would be developed in varying sizes to meet the majority of user requirements. ARPA was seeking display technologies that would have head-mounted applications. They would have high resolution, low weight, low power requirements, high brightness, good contrast, fast video refresh rates, low cost, and be easily manufactured.

ARPA and the Joint Service Working Group

Interactions with ARPA provided an opportunity to communicate the strong need for high definition small flat-panel display technologies that could be integrated into tactical military HMDs. The ARPA High Definition (Display) Systems Program provided the opportunity for DoD to leverage the research and development of these new technologies. This effort established the need for an HMD program to integrate the yet-to-be-defined miniature flat panel technologies that would be developed.

An ARPA-Joint Service Working Group (Army, Navy, Air Force and NASA) meeting was held at ARPA in the fall of 1991 to evaluate specific system and display requirements of Joint Service Programs and to assess which display technologies would address their program goals and objectives. The objectives were to compare small display requirements and system requirements for commonality. The ARPA-Joint Services brainstormed to select candidate flat panel display technologies that would have application to all DoD programs (See reference 1).

AMEL and AMLCDs - the Future Technologies

The Kopin, Planar, Standish, Honeywell (Phoenix) and Sarnoff team was selected by the ARPA Joint Services HMD Working Group to develop the Active Matrix Electroluminescent (AMEL) and Active Matrix Liquid Crystal Display (AMLCD) technologies that would be used in the next-generation HMD. The AMEL and AMLCD technologies were selected as having the potential to meet all goals and objectives of DoD HMD programs. These are the displays that were funded under the first phase of the ARPA HMD program displays.

Both AMEL and AMLCD are formed on single crystal silicon, and have on-board scanner circuitry for row and column addressing. Both are 1280 x 1024 6 bit monochrome with 24 micron pixel pitch and will operate at 60 full frames per second with contrast ratios of better than 50:1. The size of both displays is 1.1 x 1.3 inches. Because several papers have been published by Kopin and Planar on AMLCD and AMEL, this paper will not report on the details of display design and fabrication but will instead focus on the system benefits of the technologies (See reference 2 & 3).

AMEL Display Characteristics

AMEL technology, under development by Planar Systems, is a self-emissive display, requiring no backlight, which makes for a slimmer system design. It has the potential of 1000 fL brightness. AMEL is operable in wide temperature ranges. It is a rugged solid state display most suitable for man-portable applications because of its low power requirements. Because the display is opaque, the integrated circuitry and thin film transistor circuitry layout can be optimized for best electrical efficiency (i.e., transistor size, pixel shielding, grounding etc.).

Additionally, extensibility for future pixel density (higher resolution) is not restricted by inability to transmit light, or diffractive artifacts by focusing light through smaller pixels. Therefore, there is the high probability that the current 24 micron pixels could be "shrunk" to 6 microns and yield an AMEL display that has 4000 lines per inch (LPI) in a 1.1 x 1.3 inch display format. This would provide an HMD system a very wide field of view (FOV) with excellent Nyquist acuity. For example, the 1280 x 1024 AMEL with 40 degree field of view optics has 20/30 Nyquist acuity. 4000 LPI will allow for an 80 degree FOV with the 20/15 Nyquist acuity. By using white phosphor and "quading" each pixel with red, green, and blue (RGB) filters, the display will be a full color display with half the resolution of the monochrome displays (i.e. 1280 x 1024 becomes a color 640 x 512 display).

AMLCD Characteristics

AMLCD technology, under development by Kopin Corporation, is a versatile display technology because the display is capable of very high brightness. Fixed-wing aviators who require excellent contrast and brightness in "high bright" (up to 10,000 fL) ambient environments have selected AMLCD as the flat panel technology for their HMDs.

The AMLCD technology has the added advantage of being able to transmit light and can therefore be used as a projection display for large screen applications. These displays can be backlit by having a thin, low power lamp placed directly behind the display, allowing for man-portable applications. Environmental concerns regarding the effect that cold weather has on the liquid crystal material, are factors that have to be taken into consideration for certain HMD applications, such as military HMDs in unprotected environments where power requirements preclude heating the display. In military systems requiring high brightness from the displays, "off-board" lighting can illuminate the display through fiber-optics coupled to a faceplate behind the display. (The lamp technologies will be described in a following section.)

Like the AMEL displays, the AMLCD will allow for increased resolution, but the integrated circuitry layout requires more consideration, because the placement of transistors, spacers and other circuitry reduces the light transmission. FOV and resolution incremental increases have the same relationship as the AMEL. AMLCD can be colorized in two ways. One approach is similar to the AMEL approach, in that a monochrome display is filtered with red,green and blue (RGB) and has the same effect with regard to resolution.

1280 x 1024 monochrome displays become 640 x 512 RGB.

Subtractive Color Characteristics

Another color AMLCD approach, developed by Honeywell Technology Center, is a Subtractive Color approach. This allows the full resolution of the display to be retained. A 1280 x 1024 color display is formed from three 1280 x 1024 monochrome displays by using three displays in a stack. Each subtractive display requires active matrix monochrome displays with a good aperture ratio. The three displays become sandwiched with cyan, yellow, and magenta polarizers. The pixels of each display have to be perfectly registered. A spectrally refined RGB tri-band lamp is the illumination source for the displays.

Aperture ratio is important because the light has to go through each pixel of each of the three displays and through the "sandwich" of filters. Transmitted information must be free of diffractive artifacts. Think of light being transmitted through three pieces of window screen. If the three screens are perfectly aligned, light will pass through acceptably. If the AMLCDs are misaligned, this will cause a Moire effect, thus causing a loss of resolution and/or contrast as well as color separation.

Pixel Enhancement Program

In order to make monochrome displays more suited to incorporation in a color subtractive stack, ARPA funded the Pixel Enhancement Program. In this program, Sarnoff reconfigured the pixel-integrated circuitry architecture and used smaller photolithography (line) geometries to increase the aperture ratio of the display circuits. A **new pixel** is being developed to accommodate this design.

The technology developed in this program is being utilized in a rotorcraft program, which will be discussed later. The enhanced pixel will benefit monochrome as well as color displays because it will have increased light transmission capabilities.

The Combat Vehicle Crew HMD

After the ARPA-Joint Service HMD Working Group (A-JSWG) established the HMD Program and selected the display technologies, it was decided that there was the need for a systems integration of the miniature flat-panel display technologies into a prototype HMD. The combat vehicle tank commander was selected as the candidate platform for the next generation HMD system. Honeywell Corporation (Minneapolis), selected by the AJSWG as the systems integrator, began the system development program in August 1992 to design a new HMD incorporating two high-resolution flat panel display technologies: AMEL and AMLCD, a graphics processor, computer interface, and a new optical configuration for the tank application (See reference 4).

The Combat Vehicle Crew Head-Mounted Display (CVC HMD) became the "high visibility" program ensuring a systematic and concurrent engineering approach working an "unknown" from the systems packaging and electrical interface aspect, and the display developers "inventing" a technology that would have system compatibility. Together the display development team of Kopin, Planar, Standish, and David Sarnoff Research Center (Sarnoff), along with Honeywell, began the task of integrating the technology, guiding the development path to insert new display technologies into a tactical HMD system.

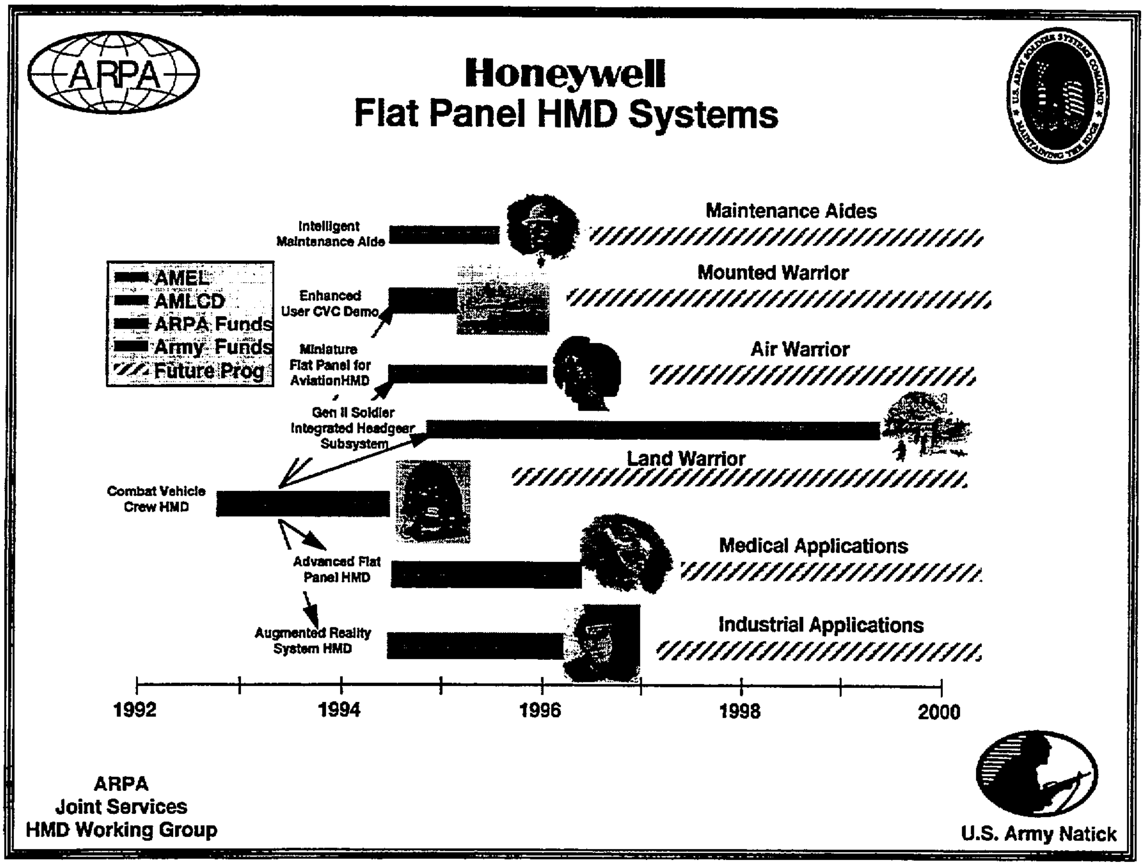
The decisions that led to the selection of the tank HMD application were as follows: the tank has on-board power management; sensors; internal/external communications; signal/image processing and a pos/nav system, so there were no man-portable concerns. Also, because tank commanders have never used an HMD, they would be more open to ideas relative to HMD configuration and the way information is displayed than other users would be (i.e. rotorcraft pilots, fixed-wing pilots). This first experience would allow some flexibility of HMD design parameters, allowing for some experimentation.

System Applications and User Issues

As the CVC HMD system began to take shape, discussions related to technology transition and human factors issues arose. The Enhanced User Evaluation and Demonstration of the CVC HMD (Enhanced User) program resulted from recognizing the technological challenge of integrating new technologies to a new user. The CVC HMD program had to consider the soldier's ability to perform tasks with the new equipment. Issues such as display formatting, simulation with displayed information, and many human factors questions had to be addressed.

In the Enhanced User program, Honeywell HMDs using Kopin Corporation 640 x 480 AMLCDs were integrated into simulators at the Mounted Warfighting Battlespace Battle Lab (MWBBL), the simulation laboratory at the Armor Center in Fort Knox, KY.

A high caliber simulation effort at Fort Knox that explores display formatting and human factors issues was executed in February 1995 to satisfy the proof of principal requirement. The displayed information is based on the MlA2 Inter-Vehicle Information System (IVIS) as a baseline. MlA2 simulators with the new (IVIS) tactical displays were installed in the MWBBL facility at Fort Knox. This has been accepted by the MWBBL at Fort Knox as the most viable approach to addressing the human factors



issues.

Enabling Technologies

As the AMEL, AMLCD, and CVC HMD programs moved forward, certain system applications and integration concerns started to be voiced by Joint Services systems experts regarding 1) the need for better lamp technologies to enhance the brightness and contrast in high-bright ambient environments, and 2) the need to filter out unnecessary color wavelengths in the lamp spectrum. Increasing the resolution in the currently funded displays to provide wider FOV in HMDs was another subject of interest. The ARPA 1993 Broad Agency Announcement (BAA) addressed these areas. Kopin Corporation was awarded a contract that contained four discreet tasks. This program, the Development of Support Technology for Color HMDs includes the following tasks:

a. Development of color filters that can be fabricated with the displays allows for perfect registration alignment with the pixels, directly benefiting AMLCD projection and HMD systems. These filters are being developed by Kopin, Taunton, MA.

b. Development of a low wattage, high performance, and spectrally refined triband metal halide lamp. The lamp, developed by ILC, Sunnyvale, CA, (as a Kopin sub-contract) is currently undergoing tests at Honeywell. It has well-defined RGB wavelengths which allow the use of thin notched polarizer filters. It is expected to provide greatly improved luminance efficiency in color AMLCDs.

c. Spacerless assembly of AMLCD stacks is being executed by Standish Industries, WI (as a Kopin sub-contract). The liquid crystal material in AMLCDs has spacers to keep the front and rear glass separated in AMLCDs. This allows the liquid crystals to move. Because spacers in high density active matrix displays block pixels, it is important to identify a process that permits an alternative. The first spacerless displays will be delivered to Kopin for examination in the Spring of 1995.

d. Kopin and Sarnoff are developing a new version of the 1280 x 1024, one-inch, 24-micron AMLCD design. This task shrinks the pixel size to a 12-micron design with finer photolithography rules. By doing this, the one-inch display becomes half the size, yielding a 1/2-inch 1280 x 1024 AMLCD. This design is currently being fabricated in the Allied Signal foundry and will be evaluated in the Spring of 1995.

AMLCD Efficiencv Improvements

Under the same ARPA BAA, Honeywell Technology Center began a program to improve AMLCD efficiency.

This program known as Backlight Efficiency Enhancement Using Non-Absorbing Polarization and Notch Polarizers for Subtractive Color Light Valves was completed in January 1995. The program included the following tasks:

a. The first task was a twelve month effort to improve the efficiency and performance of a backlight AMLCD flat panel, as well as a wide viewing angle display system. This novel approach used a pre-polarizing filter element that allows for direct efficiency gains. This technology was demonstrated at the November 1994 AJSWG meeting in Washington D.C. It will be used in both direct view and HMD systems to increase display brightness, reduce power, and improve overall color AMLCD performance.

b. The second task was a seventeen month effort to fabricate notched circular polarizers as independent films and integrate them with quarter wave retardation films in a subtractive color light valve assembly (color projection display). This included matching of the polarization wavelengths to lamp spectra. Three 640 x 480 subtractive color image sources were developed. This was demonstrated in Phoenix in January 1995. The 1280 x 1024 displays were not used because the aforementioned Pixel Enhancement program is yet to be completed.

Honeywell's Two Primary Color Analysis program was awarded under a 1994 ARPA BAA. It will define the utility of using the two primary colors (red and green) in displays used for target acquisition, maps, and other displayed data. The purpose is to determine if there is a need to have full spectrum RGB in color displays. A series of human factors studies will be included in this analysis. If it is determined that the two primary colors are adequate, as opposed to three, the analysis will lead to simplifying the development, minimizing the weight, reducing the packaging and cost of maximum resolution subtractive color displays for flat- panel HMDs.

Small fluorescent lamps under development by Flat Candle Company, Colorado Springs, CO, for application in HMDs were being supplied to Honeywell under the CVC HMD program. Later, under a 1994 ARPA BAA, Flat Candle Co. began a more comprehensive Fluorescent Lamp Development program. The three lamps under development in this program are a low luminance lamp, a high luminance lamp, and a color sequential or multicolor lamp. Flat Candle has successfully built the lamps that illuminate the active matrix liquid crystal displays (AMLCD) in the Combat Vehicle Crew HMD. The lamps to be developed will have better efficiency with less heat. The lamp under development for color will be used in lieu of color filters because it will contain RGB phosphors, which will pulse behind white display pixels. It has been noted by Flat Candle scientists that the phosphor decay time (the time it takes to cease illuminating) may be too long to pulse at the required rate for certain color display applications. The program deliverables will be evaluated in the Spring of 1995.

Enabling Technology Applications

The enabling technologies, the lamps, pre-polarizer and notched filters, spacerless AMLCD assembly, and the shrinkage of the pixel/display size significantly extended the utility of the technologies under development.

The program growth is now well on its way. The AMLCD limitations in subtractive color applications with regard to brightness and illumination have been significantly minimized. HMD systems requiring displays with excellent color gamut and high luminance efficiency are now attainable as a result of the lamp and filter development. System benefits for the resulting 1/2-inch 12-micron display will be compact HMD designs that can take advantage of the spacerless assembly with no concerns of pixel blockage. The two-primary-color analysis may lead to simplifying and reducing the costs of subtractive color HMDs.

2560 x 2048 Display Development

After the development of the 1280 x 1024 AMEL and AMLCD displays, which are undergoing redesigns to optimize the processes for pre-production in 1995, the 2560 x 2048 AMEL and AMLCD program was awarded under the 1994 ARPA BAA. This development builds on the successful 1280 x 1024 AMEL and AMLCD development program. This higher 2560 x 2048 resolution will result in systems having expanded capability by improving acuity over wider fields of view. The 12-micron display size also provides significant versatility. Many displays can be configured from a 12-micron design.

As previously mentioned, the AMEL resolution is not restricted because it is an opaque display. The increase in resolution is the direct result of shrinking and improving the pixel circuitry. These improvements will be attainable for both monochrome and color displays, thus yielding a one-inch 2560 x 2048 monochrome display and a 1280 x 1024 color display. With modifications a one-half inch 1280 x 1024 monochrome and a 640 x 480 color display may be possible.

The increase in AMLCD resolution is the direct result of shrinking and improving the pixel circuitry. Like the AMEL display, the 12-micron AMLCD design is versatile, although it may be more difficult to use a 12-micron design in a subtractive color display approach.

The 2560 x 2048 AMEL and AMLCD development is following a path similar to the 1080 x 1024 development. The 2560 x 2048 program is a 30-Month program which began in May 1994. Display deliverables are to be integrated into an HMD system in December 1996.

ARPA - Joint Service Systems

The Honeywell CVC HMD system and Enhanced User programs (previously described) were just the beginning of the transition of the ARPA HMD technology. Since that program began in 1992, many other programs have been initiated. The following is a summary of the currently funded programs:

a. The ARPA Advanced Flat Panel HMD (Honeywell) Program will develop a high-resolution, lightweight, low-power, man-portable color AMEL and AMLCD HMD system focused on military medical applications. The program is coordinated with the medical community through the U.S. Army Aeromedical Research Laboratories (USAARL), Fort Rucker, AL. The first prototype demonstrations are planned for Summer 1995.

b. The ARPA Full Immersion HMD (Kaiser Electro-Optics) Program is an HMD that "tiles" six AMLCDs per eye and will provide a high resolution wide field of view for simulation applications. The first color prototype is scheduled to be delivered in 1995.

c. The Army Miniature Flat Panel for Aviation (MFP/A Honeywell) Program is a reconfiguration of the Combat Vehicle Crew HMD. The AMEL display technology is being integrated into an HMD system that will provide digitized night/day and FLIR sensor imagery to the rotorcraft pilot. The MFP/A HMD program is recognized by the AJSWG as having the potential to overcome the technical challenges inherent in current rotorcraft HMD designs. Once developed, a series of flight tests will be conducted by the U.S. Army to determine system effectiveness as a tactical HMD system. The aircraft integration, flight evaluation, and data analysis are expected to begin in December 1995 and conclude in May 1996.

d. The Army Advanced Visionics Systems (AVS Hughes Training) Program is a U.S. Army, NASA, and United Kingdom Subtractive Color Active Matrix Liquid Crystal Display (AMLCD) wide FOV HMD program which will allow rotorcraft pilots to perform covert operations in night and daytime missions. The AVS program was formally known as the Covert Operations in Night/Day Operations in Rotorcraft (CONDOR) program. Flight tests are scheduled for early 1996.

e. The Army/ARPA Intelligent Maintenance Aid HMD (Planar Systems) Program is an HMD information management system that will allow a technician to retrieve maintenance data to diagnose and repair weapons platforms and other Army equipment with the aid of a man portable computer expert system processor. This computer based maintenance diagnostic system will be interfaced to a high resolution, lightweight, low power HMD that has a smaller AMEL image source. The system will be governed by voice transmission, and will assist in decision making capabilities to enhance performance in tactical maintenance procedures. The prototype will be demonstrated in the summer of 1995.

f. The ARPA Augmented Reality (Boeing/ Honeywell/ Virtual Vision/CMU/) Program is a high-performance, see-through binocular HMD system used in conjunction with a high accuracy head position/orientation tracker. The HMD system enables diagrams and other information on the display to be projected and stabilized on specific coordinates, appearing to the wearer almost as if it were painted there. The see-through and head tracker are the key elements of the "Augmented Reality" technology. The HMD will integrate both 1280 monochrome 640 color Active Matrix EL and LCD displays.

g. The Army Generation II Soldier System (Motorola) Program is an Advanced Technology Demonstration of a dismounted soldier system. The AMEL based Integrated Headgear Subsystem will interface with the thermal and charge~ coupled device (CCD) weapon sight, the Soldier Computer/Radio and head-mounted I CCD. The system is being developed to provide the dismounted soldier with a lightweight, mission tailorable, communication and information management system to enhance lethality, survivability and situational awareness on the battlefield.

Tactical Information Systems

There are many applications for the technologies emerging from the ARPA HMD program. Some new programs are in contract negotiation and will be awarded soon. ARPA has a program known as the Tactical Information Assistant (TIA) Program. These are described as small, portable, electronic systems that provide individual users or teams with application-specific information to enhance individuals' performance. TIAs perform the functions of computation, communication, sensing, and/or navigation and combine these with human-computer interfaces. They use displays (direct view or head mounted) to present information in a visual form. TIAs can be either stand-alone systems or serve as terminals for receiving and/or transmitting information. The focus is on providing individuals with information access devices. Some of these will have maintenance applications such as multimedia approaches capable of interrogating embedded maintenance processors and voiceactivated pictorial views of disassembly and assembly.

SUMMARY

The ARPA HMD technologies have changed the future of HMDs. The flat-panel displays and the CVC HMD system have successfully demonstrated the advantages that the technology has to offer. Weight, voltage, size, optical packaging, and overall integration offer significant advantages over CRT-based designs. Many military systems leveraging these technologies have emerged as a result of the ARPA HMD program. The dual-use applications of these miniature flat panel display technologies have increasingly wide approval because they are expected to satisfy the requirements of the military, medical, commercial, and consumer markets.

The ARPA-Joint Service Working Group has teamed successfully over the past three years to maintain HMD system prototype oversight and to refresh and expand the program with new ideas. Based on these successes, many new programs are expected to be generated to expand the HMD program even further.

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1.9 Construction Robotics

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Construction robotics has gone through a checkered history -- full of both bad and good ideas. I am going to discuss some of these and give some examples. I also want to outline some problems and opportunities for applying robotics to the construction industry.

Let's start off with the bad ideas. If you look at a lot of what is going on in research laboratories, you'll find robots trying to use hand tools, such as hammers and screw drivers. In one laboratory in Japan, I saw a two armed robot using a brace-and-bit -- trying to drill a hole in a board. Needless to say, the economic value of that kind of project is zero.

The literature is full of attempts to develop robot masons, plumbers, and carpenters without actually understanding what real human masons, plumbers, and carpenters actually do most of the time. Most of the work in laying bricks is not setting the bricks in place, but building the scaffolding, mixing the mortar, and carrying the bricks to where they are to be used. Also there is the detail of putting the mortar on the bricks before they are set. Most robot masons ignore all of these real problems, and worry only about setting the bricks in place. This is less than 1/10th of the job.

A professor at MIT recently developed a robotic system for installing drywall. However, if you watch a crew of skilled humans putting up drywall, and compare their performance with what a robot can do, you will understand that humans can put up drywall 10 times faster than any robot will in this century, and maybe in the next.

The idea frequently is put forward of unmanned robotic construction equipment. It doesn't take much thought to realize that turning a robot bulldozer, or a robot back hoe, loose on a construction site without a human being in it, is really a bad idea. It would be a disaster waiting to happen.

Many of the bad ideas involve robots doing tasks that require visual perception. This is largely an unsolved problem even in the laboratory. It is totally impractical on a construction site with bright sunlight, rain, clouds. Any time you think about making robots do what humans do with their hands, legs, and eyes -- things that require tactile dexterity, or agile mobility such as climbing ladders or scaffolding, or seeing, or common sense reasoning -- think again. Most of the bad ideas involve competing with the human hand, or the human eye, or the human ability to move around a complex environment.

Current robotics technology is so far from human capabilities in these areas, that making such proposals destroys the credibility of anyone suggesting using robotics on the construction site.

However, there are many ideas that do have merit. One is site integration. Site integration enables bringing together knowledge from the design database with in-situ metrology. Site integration involves keeping track of inventory, scheduling operations, and using data from CAD design systems to generate control instructions for machinery to do things like automatic cut-off of materials.

A good example of the latter is the manufacture of roof trusses. Data from the CAD design of the shape of the roof automatically generates settings for the saw blades and stops to cut boards for roof trusses. These cut pieces are then placed in computer controlled jigs where they are joined into truss members. This is quite effective technology that has been used with very good effect to generate a big economic pay-off. I don't have the numbers, but my guess is that a very large percentage of roof trusses are now built this way.

Modular construction is carrying this idea yet further. Factory built modular housing -- using CAD data to cut and fit piping, and build wall panels, and windows and doors, and bathroom modules -- has become quite economical. Of course, when the modules get large, there is a transportation problem. There are also tolerance problems in getting modules to fit together so that the electrical, and plumbing, and heating ducts fit together.

There is also some real potential for intelligent vehicles and manipulators that are not unmanned. Such systems assist the human operator in accomplishing his task, in digging in the right place, in maintaining position accuracy, in preventing tip-over or overload. The intelligent machine makes it easy for the operator to know where he is and what he should do to improve his performance and prevent mistakes.

I want to talk a little bit about RoboCrane and show a movie. This device has many potential applications for placing forms, erecting steel or concrete framework, placing rebar and concrete, and using tools for finishing, painting, paint stripping.

Another potential application is bridge inspection and maintenance. There are around 300,000 bridges in the United States that are need of repair. There is enormous potential for building robotic devices that can address this problem.

The bottom line here is that to make construction automation work, you've got to pick real problems with major cost benefits where the introduction of robotics will produce an immediate substantial economic benefit.

I have 5 tapes that I'm going to play segments from to show some things you may find interesting.

The first one is the Shimizu jack-up roof system. Shown here is a big office building in Tokyo. The top section is a work area with a crane built into the roof. As the building goes up, the roof with the work area is jacked up. This approach provides an indoor environment for the workers so that they can work in rainy and windy weather. It makes the work-site easy to manage. In the corners are the jacks that lift roof and there are rails on the roof that allow cranes to move out beyond the edge of the buildings so they can unload trucks from down below. The crane is computer controlled. There is a vertical monitoring system for setting and aligning the columns as the roof is jacked up. The incoming loads go up the side of the building with sufficient stability that it doesn't bang into the side of the building. Without disconnecting the load, it goes right into the construction area and is placed into position.

Mike Sims, NASA: Is this now controlled as each one comes up, are they hand controlling it or is it all automated?

Jim Albus, NIST: It's not clear from the video. There is a control room where the cranes are controlled. But I have the feeling that there are people manually operating the crane.

Once the beams are in position and lined up, then a welding robot welds the beams into position. This is a floor panel coming into place. It's just a pre-fabricated floor panel, of modular construction. Once it's in position then this creates the forms for pouring the concrete. The floors are poured concrete. The cranes have rotary positioning and there are alignment mechanisms so that the parts come down and fit over alignment jigs and once they are in position you can see the sealant that was already in place.

Now this is jack up mechanism. Once they finish a floor, then the whole system is jacked up for the next floor. Once the building is finished, they take down the big structure on the top and then lower the sides the same way all of the other material was brought up. The roof panels then fold up.

This second clip is from Takanaka corporation. This is from about 5 or 6 years ago. This is a much more limited application. This is a rebar placement robot with a boom and a gripper. This is a picture of the robot working on a nuclear power plant. This shows the gripper and a feeder mechanism that feeds the rebar. The gripper mechanism has pitch and roll capabilities so it can pick and turn the rebar vertically. This robot is not computer controlled. There is an operator walking around with a radio controlled joystick. Once the rebar is in position a worker ties it off.

This third clip is another robotic system designed by Advanced Technology Research that I think has some potential, for bridge inspection. This particular robot is designed to crawl through the interior of double hull tankers, or double hull combatant ships. There is a couple of issues here that are significant. These are three foot square box beams. The robot is working inside to inspect for rust, to sand blast the rust clean, and to re-paint. This shows some of the computer graphics that were used in the design of the robot.

The operator can see displayed the status of the robot and where it is within the beam. He has stored pictures of rust samples to compare with the rust that he sees via a TV camera. The operator can thus classify the degree of rust, and can outline the areas where the rust is. Then

depending on what type of rust is encountered, the robot will go through the proper sequence for sand blasting that type of rust.

The operator can then go back to see the rust spot after its been cleaned. If it is not completely clean, he can go back and do it again. The robot will then automatically re-paint the area.

This is the operator's workstation. The operator doesn't actually control any of these detailed motions. He simply indicates where he wants the robot to go. He just points and clicks. The camera lens retracts and is covered during the painting and sand blasting operation.

A fourth clip shows work that was done at the construction automation research laboratory at North Carolina State University. This shows a big arm that comes down under the bridge and has the nozzle for sand blasting, re-painting, and inspection. The arm is mounted on the back of a truck. I think this is a conventional commercial arm. This shot shows a containment mechanism which goes up underneath the bridge and inflates so as to contain the debris. I think one of the most notable things about this was that it was done by students on a very low budget.

The last thing I want to show you is some of the work that we're doing here at NIST in the area of robot cranes. This particular version of the robot crane is for the rapid construction of temporary bridges. It uses a conventional straddle crane with the boom out in front which allows us to pick up modular bridge sections launch them into position and control them at all six degrees of freedom. We can move the bridge sections forward and lower them into position very precisely. We think we can hold a tolerance of better than a quarter of an inch in the alignment of the bridge sections.

For launching out over long areas we have a maypole suspension system. The RoboCrane is quite light so that the bridge doesn't have to be any heavier than for normal automobile traffic. Therefore, the bridge doesn't have to be built stronger than necessary in order to support the crane during construction. The crane is prevented from tipping over by fastening it to the bridge when it is launching sections. These sections are about fifteen tons and they are forty feet long. This is a computer simulation of the truck coming in with modular bridge sections stacked on the back of the truck. RoboCrane assembles the modular bridge sections and then picks them up and launches them forward, putting them into position. Each section is forty feet long and thirty two feet wide. The entire bridge is launched in three sections. The second and third launch contain the deck plates and guard rails.

Our estimate is that each assembly and launch sequence is about a 20-minute operation. We estimate we can assemble and set forty feet of bridge per hour. This is a 1/6 scale model which shows how the operator has a joystick box. There are seven winches that are under computer control so that the operator simply pushes the joystick in the direction that he wants the bridge to move and it goes in that direction. You can cause it to roll, pitch, to yaw and to move in xyz. This is showing some of the assembly sequence where the bridge section is moving forward and then being placed into position with the operator being able to control it in all six degrees of freedom and align bolt holes. If you are here tomorrow you can get a live demonstration.

We also have a 1/16 scale model where we built a whole bunch of sections. The 1/6 scale model is for testing the computer controls. We will not do a full scale demonstration until there exists a construction project with a contractor who has won a bid and is actually going to build a bridge.

That brings me to my last slide which deals with the problems and opportunities in developing advanced automation for construction. One of the problems is the lack of vertical integration in the construction industry in this country. As most of you know, in Japan there are vertically integrated construction companies where the architects, the engineers, the researchers, the construction crews, and in some cases, even the construction equipment manufacturer, all belong to the same company. These companies are owned by a consortium of banks with a very long view point. So it is almost as if the federal reserve owned the construction company and was willing to finance the research and development of advanced construction technology. So the Japanese can take a very long view point and plan on amortizing this kind of research over many projects. In the United States, it is necessary on every job to go with the low bidder, and once a contract is awarded, the contractor must start working in about a month or two. It is often necessary to be able to pay back research and development costs and equipment procurement all on the first job -- and still be low bidder.

This presents a huge hurdle to getting advanced technology onto the construction site. The result is that the construction industry in this country does almost no research and development. This is not because they are stupid people, or because they are crass or short sighted. It is simply because those are the economic facts of life in the construction industry. Naturally, this produces a low rate of productivity growth.

Of course, there are other factors such as labor unions, building codes and standards. But, my feeling is, these are not the principal problem. I believe that the big problem is that any innovation has to pay off on the first job, for the low bidder.

The American system makes for good short term profitability, but it doesn't lead to long term view points and productivity growth which requires patience. In order to develop these kinds of technologies, you can't expect it to pay off on the first job and you can't do all your research and development in the two month period between the time that you actually have some money and the time that you have to start the job.

I believe there is a huge potential for technology advance in the construction industry. That is not by any means a unique, or a particularly inspired, view point. I think almost everybody sees that. There is potential for leveraging technology from other industries particularly manufacturing industries. There is a lot of technology out there that we've talked about today. But it requires the right economic incentives to move it in the market place. There are a lot of disincentives that keep it from getting into the market place. One of the things that we've discovered when we were working with Dr. Woo on the Federal Highway Department, talking to contractors, they say "we can work faster and better. All that we need are economic incentives to make it worth our while."

Jobs that have high incentives for getting finished earlier, do in fact get finished earlier. It is not that people can't do this, its just that the economic incentives for technological development and for improving productivity are lacking. Hopefully that means that there's a good rationale for a government agency like NIST, and the Corps of Engineers, and other people in the government that are interested in construction, to try to help in technology development. That is one of the reasons why we are here, to try to work with industry, try to understand what the most productive areas are for addressing with the few research dollars that we hope we are going to have.

Bob McClelland, Fluor Daniel: *I guess you've kind of alluded thatNIST can help with some of this technology transfer to private industry. What can NIST do in government contracts to encourage the use of the new technology by convincing government agencies to award contracts on the basis of trying this technology rather than just being the low bidder?*

Jim Albus, NIST: That is a good question, I'm not sure that NIST can do a lot. But, I think the Federal Highway Administration already has a number of incentive programs -- some experimental programs. There are some set-asides for experimental technologies. Dr. Woo do you want to comment on that?

Charles Woo, FHWA: *As an example, following the earthquake in Los Angeles, if you finished the job ahead of time you got a significant bonus. We also have demonstration projects to demonstrate new technology for use by the contractors, states.*

Bob McClelland, Fluor Daniel: *think personally that the government's has to give some incentive to try this new technology because construction companies are going to use the technology they know works. They are not going to stick their necks out and risk their business.*

Jim Albus, NIST: That's right, you're betting your company. If you're going to try a RoboCrane® that is supposed to build your bridge forty feet an hour and it doesn't happen ...

Bob McClelland, Fluor Daniel: *even if it's a company like Fluor Daniel that has tremendous assets behind it, the project manager is not going to stick his neck out because it is his career.*

Jim Albus, NIST: That's right, its not a good career development path to go way over on cost or time.

Bob McClelland, Fluor Daniel: *Some help has got to come from the government, maybe overlooking the requirement for absolute low bidder and award the job based* *on using this new technology even though it may cost more initially just to develop it.*

Jim Albus, NIST: I agree. There may be some way that this kind of issue could become embedded in this initiative.

Clay Claassen, Bechtel: *Along that same viewpoint, some of the areas we've seen where contractors like ourselves, engineer/constructors can try new things, innovate and so forth, is working for private clients who are looking at projects -- not just on the construction costs alone as far as the award -- but on the full plant life cycle costs, where engineering construction is just the front end. They've got to operate it for the next thirty years. This then, allows a contractor to introduce new ideas. It may cost more in the construction, but will save significant amount of money during the operation and maintenance of that facility over the next thirty years.*

Jim Albus, NIST: I think that's true, but I'm not sure that that is a solution to construction equipment advances in robotics, but it certainly has a lot to do with maybe various construction materials and issues such as as-built databases and things like that, where the maintenance becomes quicker and easier.

Gershon Weltman, Perceptronics: *I was just following up on this idea of incentives and what NIST might do. If you take the analogous case of the fact that in defense contracts people receive a ten percent premium or incentive on their bid if they are economically disadvantaged or woman-owned or minority-owned, you could go the other way and say you get a ten percent advantage if you are technologically advanced ,even though it might not pay off on this particular job. If NIST could be the arbiter of who qualifies for technologically advanced proposals, since you are in fact dealing with the technology that is being proposed. So I think if someone suggests that type of mechanism it really doesn't change things, it just gets you to say OK here is what you did, we multiply it by .9 to find out what your actual bid was.*

Jim Albus, NIST: I agree. I think those kinds of innovative concepts are something we need. We need to do something different than what we are doing right now because we are not going to get there with the present set up.

John Schlecht, Iron Working Institute: *First of all, back to the future. Vertical integration: 75 years ago Bethlehem Steel designed, rolled, fabricated, and erected a bridge, as opposed to all of this specialized work we have today. The main point that I want to make is that I believe that government does have the wherewithall to do this and if I can kind of re--spin what Fluor Daniel and Bechtel are saying: The government can create this vertical integration by requiring the prime contractor to perhaps be a design-builder who provides design services and who also does his own construction work as opposed to subbing everything out. And borrowing from the defense industry, the government,under that scenario ,could provide money up front to his design-constructor as a part of what would be called mobilization. They do it all the time on these big defense contracts where a private company doesn't have the money to do it on their own and they actually fund some of the research to be done. So ,without changing things all that much, I think the government could require certain design initiatives, to look at different things on a design-build job where the contractor provided his own work as opposed to* *subbing everything out to the 150 cheapest subcontractors. And that would force the vertical integration and would also make possible this technological progress that we're looking for.*

Jim Albus, NIST: I think you're right, but I'm not very optimistic about that particular solution. In fact, it seems right now like the manufacturing industry is moving in the other direction. This whole business of lean manufacturing is you get rid of in house capability and out-source. Its almost like we are trying to make manufacturing like the construction industry is. Where the manufacturer only does one thing and he does it very well and he subs everything else out with just-in-time delivery and so forth. So, I am afraid the tide is moving in the other direction. I'm not quite sure what the conglomeration of political forces would be that would be able to stand against that.

Ken Goodwin, NIST: *I'd like to say that in the 60's when we looked at this, we did propose that the federal construction budget be used to provide incentives for different construction projects and introduction of new technology. The military construction of course is falling off a bit right now. GSA has done a number of projects along that line and we probably need to revisit that.*

Ron Levandowski, Honeywell: *I think the concept of how the military does it, I don't think that's very accurate. What the military does is, you are allowed to write off a small percentage, get reimbursed on your next contract -- 2% -- that goes into IR&D. Just on the helmet I described earlier we spent between $500,000 and $1,000,000 each year in helmet monitor display IR&D, research and development. And you tell the construction company we are willing to do that kind of thing -- there is ATP money right now.*

Jim Albus, NIST: What's happening on TRP's is that there are consortiums of companies that get together and share knowledge and all are going to benefit -- if this goes forward we're all going to make a bunch of money. But, we're putting in half the money ourselves. There are four hundred million dollars in the ATP's and if construction companies are willing to form a consortium and put up half of the money they'll get half that back. I think the mechanisms are in place if you can get a consortium together and say, "we're willing to put some research money and a small amount of our profits in now."

If you heard Jim Hill say this morning say that one of the reasons that the construction ATP program is having a hard time getting off the ground, is its having a hard time finding anybody who will even take the matching offer.

Ken Goodwin, NIST: *In the general competition of 250 proposals, this month we only received ,I think ,about 4 in construction.*

Jim Albus, NIST: So we do have a problem.

Ken Reinschmidt, Stone & Webster: *None of that ATP money is in construction and you don't stand a chance in the general competition. If Jim can get a program focused on construction then there is a possibility. Looking at the statistics, you might as well bet your money on the ponies than on the general ATP competition. I've put in proposals that got wiped out.*

Jim Albus, NIST: You're right. The general competition hit rate is down there about 10%. When you're competing with really hot things like bio-engineering and stuff like that which is real sexy and all, the idea of concrete and steel competing with that is tough.

1.10 Automated Excavation

Chuck Schaidle
Caterpillar

This a unique experience for me because Caterpillar being a 14 plus billion dollar a year sales company, multi national, very clearly the leader in our industry, have many oportunities to talk to groups of government people and university people and small company people. They all ask for our opinion and our insight and basically our concurrence with what they're doing. Generally at the break I find one or two kindred souls and we ask ourselves how are we going to get these guys back on track. That is not the case here. The vision of the group here this morning and this afternoon has been right along the lines of the direction we're going.

I want to share with you some of those directions. It's kind of scary the similarity, even in management. Ernie this morning, his background in manufacturing. Our current Vice President for R&D comes out of our manufacturing operation; he ran a manufacturing plant in Mexico for a number of years, was a manufacturing director. He looks at a lot of things that we're doing in construction and earth moving and says, "That's a plant, an automated plant, without a roof on it." I think he's right. There are a lot of similarities to what Ernie's talking about.

In one sense, I'm going to narrow down here and talk about only one phase of construction — it's really the only phase that Caterpillar deals with, and that is earth moving. So, my comments apply specifically to that. Eric Lundberg talked about computer-aided construction. Well this is computer-aided earth moving which is a subset of construction. Computer-aided earth moving systems apply to tying planning and operations together. This is all part of what we talk about as our total vision, how we see our products being used in what we see as earth moving in the information age.

As our industry goes through the type of revolution that retailing has gone through, that banking and finance has gone through, where you link an industry to computers and computer data bases and to communications. The reason why our industry has been a late developer is fundamental to one of the things that Mike talked about this morning. That is, for our industry to link to computers and to communications and the data bases there is a need to know where things are at. Very accurately, very fast, basically in real-time. We've never been able to do that out in the earth moving environment.

The thing that brought on the information revolution in retailing was bar codes and laser scanners... knowing what things are. What brought on the revolution in banking was a nice little magnetic strip on the back of these plastic cards that we run through ATMs. And what we see causing this revolution in our industry are things like GPS, the laser positioning system, some of the RF positioning systems.

Now, just briefly, a couple of people have asked me what we're doing in monitoring diagnostics and prognostics. A lot of our machines have 65 plus sensors — a lot of data that if you know how to analyze it you can tell an awful lot about the health of that machine -- when it needs to be repaired, whether it needs to be stopped immediately, the cost of continuing to run it, etc. There is basic communications to and from the machine, there is management of the machines. But, an awful lot of what I'd like to talk about this afternoon deals with planning and operations. I'd like to come back to Jim's chart here and really work from the bottom up on this.

In the earth moving part of construction there are huge economic incentives to our customers in saving material usage. If you can reduce those costs, there are big incentives to implementing this technology. We at Caterpillar are very keen on leveraging technology. I don't want to spend half a million dollars a year developing a computer screen that I can get from Honeywell. I don't want to spend a whole bunch of money developing computer software for managing 3D data bases if I can get that from AutoCAD. I don't want to develop a good positioning system if I can get that from SPSI or if I can get GPS from Trimble, or Leica or Ashtec, or Novetel — I think there are 52 producers of GPS systems right now.

There is a huge potential for this technology where it stands today and where we see it going.

We talked about the ability to take Ernie's trench model and put it on a machine. Right, he needs a workstation to run that. Well, computers are coming down at 40% per year compounded, and in the recent years it has been running 55% per year. Those PCs today were workstations not very long ago. So, you have to be thinking in that environment. Don't limit ourselves by where technology is today.

Human's acceptance of technology is not really a problem. We've explored that a lot with our customers. It's not really a problem for operators to pick these things up and use them. We had a system out (I'll show you an example of it here later), where the operator had two years of education. I don't mean two years of college or high school. He had two years of education and he picked this system up, and he's running a machine with satellites and stored data bases. Now, his twelve year old daughter has a PC with a CD ROM and ... it is happening. We don't see the acceptance by operator or the acceptance of our customers of technology or of skill-enhanced machines or even going all the way to autonomous machines in some environments as being unreasonable.

Let's talk about site planning. What's going on today is computer-based site planning. Whether it's a commercial site or whether it's a highway. And then when we got out to the field we start kind of reverting back to wooden stakes in the ground and pieces of paper that get wet and dirty. We haven't been able to link into that data base. That is a massive data base. Whether it exists in the contractors pick-up truck, or his home office in town, or the main mine office in London, or anywhere in the world. You need to be able to link into that. We want to take that data right out to that machine in real time and not only take the data out, but when that machine accomplishes something have it known to the main office what was accomplished.

I'd like to talk now about what we've been doing in machine automation and will start with some of our work in GPS. Someone talked about hardening these systems and putting it out on the machine and packaging it. Here's our system. It is a system that is common. We see it as common for every single machine we build, and by the way we see these technologies going on every machine we build.

It doesn't have the same value on a $35,000 backhoe as it does on a $3 million front shovel, so naturally you're going to start on the front shovel, and over the years move it down to small machines as the prices come down. The key to bringing the prices down, like with electronics, is to get the volume up. One way to get the volume up is keep everything the same whether it's on a backhoe loader or big truck or what have you. Now what's here and I'll take these boxes apart a little bit. This is a radio antenna for RF link to receive differential corrections. In many cases also to transmit data on and off board. The GPS antenna; GPS electronics, and computer and our information system.

GPS is just the position input into that information system. If I open up the information system box ... yes, these are hardened. It fell off the tractor I think three times in the last month; from about 10 foot up. LCD color screen — needs to be color. We are going to move entirely too much data to that operator. I think you'll appreciate that. One of the ways that you convey data information to operators is in color. If you have a lot of data, if you have a lot of information to present to him, you've got to go to color. That's a pretty big screen—10-inch diagonal. We need brightness. You need to see it in bright sunlight. Most of our machines run around the clock, and so you have to be able to read this screen at night as well.

Illumination ratios of 1000 to 1 are not out of the spec. You can turn them up and down that much. 40 meg of flash memory. Buried in here is a single board pc. Radio data link running now at 9600 baud and pretty quick going to go to 19200 baud. Technology link. This is the GPS box. Inside here is a 12 channel real time on the fly GPS system. We are really independent of whose GPS card that is. All we need is x, y and z and time. Leverage: we are not going to build that box. It's going to be Trimble, Novatel, Ashtec, whoever. Motorola radio, maybe it's going to be Ericson, GE or AT&T, Aerodyne. Maybe it's going to be a power PC; maybe its going to be an INTEL chip in there; maybe Seagate disk storage?

We are packaging our own electronics. We have yet to find anyone who knows how to package electronics for our kind of environment. So you can spray the box down with a water hose; it will run in the temperature environments that we need it to run in (in the shock and vibration environments). So what do we do with this box of electronics? We put it on a tractor.

Q. those are using 400 megahertz?

Chuck Schaidle, Caterpillar: Yes, that's our national band. We have three frequencies that we are authorized anywhere in the U.S. to use. That's what we run in when we're doing all our work.

Put the screen in the cab of a dozer. We put some data on that screen. It's different data if it's a bulldozer or different data if it's a hydraulic excavator, but it runs on that same hardware. It runs with the same database management system. The basic system that we use to manage the topographic data and all the layers of information that are stored in there are the same. The display software that turns the system into a dozer system versus an excavator system — that differs from machine to machine.

Gershon Weltman, Perceptronics: *I think your are one step ahead of the M1-A2. I don't think they have color. You pay for color. I'll be honest.*

Chuck Schaidle, Caterpillar: What I would like to do is show you a video of the system in action. This is an example of the dozer system. You are going to see an integration here of a lot of the technologies that we talked about. We took the hardware and put it on the dozer and drove around the site and measured, surveying in real time. I put this original topography into an AutoCAD system and planned a highway using commercially available cut and fill software. It told us that you have to cut this area, and you have to fill what's in blue. We then took those two pieces of data, the original and planned topographies, and loaded them on the hardware that you saw on the previous screen.

This is what's displayed on the screen in the cab of the dozer. Notice there are no survey stakes or grade stakes anywhere on the site. The only way the operator knows what he is supposed to be cutting — first of all, the only way he knows where he is supposed to be working is look at this top down plan view of the site, the little horizontal, white line is the bulldozer blade. The long icon out in front of the dozer blade shows what's in view in this bottom view which is a cross-section along that icon. The top line here is the existing topography and the blue line is the design. So this is what exists and what he's trying to produce. The system tells him how deep to be cutting. In making the transition from the cut area, the red area, to the blue area you'll see the tractor now moved out into the fill area. In fact we have made several passes here, and he's back making another pass. When we have made a pass, we shade it to give him visual correlation between what he sees on the screen and what he sees out in the real world. He knows he's got a cut here. He also knows that he has to cut deeper because it's still red.

Now he's back in the same cut. Notice he's down 18 inches or so. It's a depth that, without this system, he would have to be looking at a flag or a stake with some numbers written on the side of it saying be 18 inches below this line. He would have to keep judging that. He just cut an area to where he has the existing topography now worked to grade. When we have an area that's at grade; it's shaded a different color. It shows up white on the screen.

Kent Reed,NIST: How does the operator know what direction and attitude he's got?

Chuck Schaidle, Caterpillar: If he changes direction he'll see it. You can see him lining up there.

Kent Reed,NIST: But GPS doesn't directly provide that?

Chuck Schaidle, Caterpillar: It does if you keep track of where you were, you have velocity vectors and can integrate.

Kent Reed:, NIST : If you don't move, you don't know which direction your going in.

Chuck Schaidle, Caterpillar: That's correct. Unless you put two antennas on.

Now he's taking a gouge here. We've asked him to go into the area that he had cut to grade and cut deeper and you have the gouge there. Automatically the computer keeps track of the difference between the design and the real or existing topography. It also changes the scale so that at any time both the existing and planned lines are always in view on the screen.

Jim Albus, NIST: The crown can't show up on the screen?

Chuck Schaidle, Caterpillar: Only if he drives over it or you put the antenna on the blade. Watch this change. You'll see a very rapid change. This icon out in front of the machine — we treat that just as you would on a work station if you went and said give me the cross section between this point and that point with a mouse or a pen or what have you. Every second it is displaying a cross section.

Jim Albus,NIST: If you've made a pile of dirt in front of you, how would you know how high that pile would be?

Chuck Schaidle, Caterpillar: If you don't drive over it you won't know what it is; that's right.

Jim Albus, NIST: But you could with other sensors. You could have a laser sensor that sensed that and just added that to your cross section.

Chuck Schaidle, Caterpillar: Yes.

Milt Gore, DuPont: It was said earlier that with the differential GPS and the phase -differential GPS that sometimes you couldn't get better than about a meter resolution.

Chuck Schaidle, Caterpillar: Sometimes you can't. If you have less than four satellites, you can't. If you lose lock on those satellites, then during the time you are reacquiring them you may drop back to a code solution and there are times when you don't have four satellites available, you will not be able to get the high accuracy solutions.

Milt Goree, DuPont: Does that necessitate going out and surveying what you've done.

Chuck Schaidle, Caterpillar: Maybe, maybe not. It certainly necessitates keeping track of when you have good data. If I know I have good data, I record it. If I lose high accuracy when I'm trying to acquire data, then I sure can't record low accuracy data.

Bob King, CSM: *Would you just stop then and wait until you get a lock again?*

Chuck Schaidle, Caterpillar: In most of our applications, that's unacceptable. You've got to be locking up within well under a minute.

Bob King, CSM: *How does the operator being on the bulldozer help the operation in this case?*

Chuck Schaidle, Caterpillar: Well, in a whole lot of ways. If you take the operator off the machine, you've got to add a lot additional electronics to control the blade.

Now let's talk about commercial opportunities. There are about 10,000,000 pieces of construction equipment running today that nobody's going to go back and put all electronics on it to control it. But they would go back and put an information system on there to improve the efficiency of that operator. Second, if you take the operator totally off, then you've got to not only control the blade, you've got to steer the machine and then you've got to do another really big task which you alluded to. You've got to sense the noise and the vibration and the sound to figure out if the thing is running properly. You've got to do diagnostics and prognostics.

Plus there is the whole safety issue. So it's clear that there are huge opportunities for these technologies in providing information to machines used by machines with operators. There are huge opportunities by going to the next step of giving the guy skill-enhanced controls ... taking away some of the functions from the operators and then as you look down the road far enough in the right environments, take the operator all the way off the machine.

Bob King, CSM: *Theoretically,to make the cut that you're trying to do now,an intelligent system position of the blade and following and just reading that map could pretty well do it with the operator monitoring to manage by exception. That wouldn't be much of a control system; sort of an analogy of an auto pilot with the pilot standing by.*

Chuck Schaidle, Caterpillar: Yes, that's right. Part of our vision is tying planning and operations together and the next step is controls. The evolution of controls is multi-step, going from information systems, to taking away a few of the functions, to controlling single machines, and to controlling fleets of machines.

Bob King, CSM: *If that's true however, then the information displayed to the operator could be simplified so he might have to be integrating less information there and it would be reduced to maybe something like where your blade should be and how fast you're moving forward. The autopilot would take care of the rest.*

Chuck Schaidle, Caterpillar: Absolutely.

Bob King, CSM: *Move forward on this line. It might take the fun out of it. How did the operators react?*
Chuck Schaidle, Caterpillar: The opera-

tor, this guy that was running that machine after 20 minutes said,"I don't know why you have me raising and lowering the blade. The machine should raise and lower the blade." And there's no question that that's the way things are going.

Eric Lundberg, SPSI: Any idea for what type of productivity increase that this system provided from a standard?

Chuck Schaidle, Caterpillar: No. In this particular application, it's not so much a productivity increase as it is a safety issue and a value of real-time information and some manpower reduction — getting surveyors out of the area. But that's a good lead-in to this chart which says, "What are we after here for our customer?" We're after lowering his cost. These systems will do that in a number of ways. In some applications for some machines, there are single items on here that will way more than pay for these systems. In other applications, you are going to need a combination of these values. Let's just talk about the video operation; you've reduced the human effort. You haven't had to go out there and stake; you haven't had to go out there and survey. You've got a real-time survey which may mean I can get paid for the job when it's partially finished without going back and resurveying. I have documentation of what I've completed. I should make fewer mistakes. There should be fewer times that I've cut too deep or I get off track. If a stake is removed on a construction site, an approximate round figure for what it costs a contractor to go out and replace it is $50. So, you can reduce some costs in a number of ways.

In this application we are not really doing much to improve the utilization of the machine. The job quality for a dozer is not a real fine accurate machine, but if he were doing finish grading, if that was a motor grader instead of a dozer and then the difference between cutting too deep by an inch and needing to go and put aggregate in when you could have left the original soil there can be the profit margin for the initial contract.

Milt Gore, DuPont: What about full-time operation? You could do this at night and you wouldn't need vision to do it?

Chuck Schaidle, Caterpillar: Yes. Here are some possible NIST roles that we see. The databases that we use, we would like it to come right out of the contractors/owners/clients plans. We would like it to go right onto that machine through AutoCAD or whatever else it is. We would like him not to have to buy specific software to do that in order to work on our machine. Database standardization may be a role for NIST.

GPS: There needs to be some standards established. That industry is still sorting itself out. There needs to be some GPS test procedures. What actually do people mean by on-the-fly real-time phase GPS? Certainly GPS is not going to work everywhere to the kind of accuracies that you need in all cases. So, we need to support augmenting it with lasers, radios or what have you. I'd be glad to answer other questions.

Jim Albus, NIST: Could you say something about autonomous trucks?

Chuck Schaidle, Caterpillar: I can say something about autonomous machines. Autonomous machines are certainly part of our vision. If you think about it, an autonomous machine is going to need information. It is going to need to know what it is supposed to do out there on the site. So the first step towards autonomous machines is providing the right information in real time on the machine and then the next step is to start taking away some of the functions. Now it turns out that, once a truck is going down the road, the operator really has only two functions. He has to steer it and he has to listen for something going wrong. We are already monitoring the health of the machine. We are already doing that. To implement an autonomous truck, all you have to do is steer it. It's easier than other machines.

Bob King, CSM: *But haven't you done some and tried them in mines?*

Chuck Schaidle, Caterpillar: All I can show you today is what we have publicly disclosed. There's a lot of research going on. We're pursuing autonomy on trucks and other things as well. As I say, all these things build, if it was just for autonomy out there by itself, we probably wouldn't be pursuing it. But autonomy is a driver of our technology. You set your goal to say that "we're going to run this machine autonomously," then all these other things fall into place and we see huge commercial advantages for all these other things. And if we didn't see that, we wouldn't pursue autonomy. And we wouldn't pursue autonomy if we didn't see some commercial value in autonomy at some point in the future as well.

Jim Albus, NIST: *Would you comment a little bit more on the research. First off, you don't really build things. You build machines to build things. You're not a construction contractor. My feeling is that people who build machines actually have a better research record than the people who are building buildings. How many, I mean, there are CATs and Deere and there's a few other big companies and when I put that slide up there about the lack of R&D, I certainly wasn't thinking about CAT. It seems to me that Caterpillar and a few other big equipment companies are not really — I mean, they are doing fine and I certainly wouldn't have put that up if I were thinking about Caterpillar. Would you comment a little bit about the research in the other areas.*

Chuck Schaidle, Caterpillar: Some of our customers are the guy who owns a backhoe loader and if it doesn't run this week, he doesn't get paid, he's doing absolutely zero research. So it varies from that extreme to the industry that is doing the most, the mining industry. Roughly 30% of our sales go to the mining industry. These are multi-billion dollar companies with a very long-term perspective. Typically they are multi-national and they do a significant amount of research. In many cases, we have very close working relationships with these people. There are other people such as Fluor Daniel, and Bechtel, who are running some very significant research programs and projects. The waste industries are doing pretty well, driven primarily by the environmental need to know when things are leaking, needing to know where they put the liner, where they put specific waste. You give a trucking company a GPS sensor and send them out to the land fill and you've got a record of exactly where that truck dumped. We looked across our market segments — whether it's the backhoe loader guy digging and breaking a utility line.

There's no reason for that. Every machine, every industry... needs this onboard information. If we can get the volume up and the cost down, there's a clear applicantion. There are some applications even at today's high cost.

I'll be glad to talk to anybody about ideas or technology you have and things we can do together.

1.11 Virtual Site Representation

Clay Claassen
Bechtel

A lot has been discussed this morning and this afternoon on some of the thinking in government and academia and so forth on automation and robotics in construction. In listening to a lot of what's been discussed, I think I'm going to shift my talk just slightly. What I'd like to do is describe a few things that we've done within Bechtel in the areas of automation and I guess you'd say preparation for the use of robotics in construction.

But then also to fill in the gaps a little bit from a constructor's viewpoint, I guess you'd say a user's viewpoint, of what to us seems to be important in the way of automation and robotics in our industry. First, just to kind of describe some of the things that we've done in this area and not necessarily just as far as what we feel is important to ourselves, our own company, but things that we've done that seem to be in line with what appears of interest in the rest of the U.S. industry.

Just a couple of examples. In recent years, two programs that we've worked on that we're currently applying to our projects; one we call ALPS system, it's a crane rigging program that becomes a tool for our certified crane rigging engineers on projects. It's an automation tool that significantly speeds up their time in planning out heavy lifts. What we're talking about are lifts on construction sites that are 50 tons and greater, up to several hundred tons and beyond that. One of the driving forces in putting together a program like this was from the safety standpoint trying to alleviate the traditional approach of days and days and sometimes even weeks of calculations going through various lift planning scenarios to identify an optimum plan for a heavy lift and also selecting the proper cranes for lift and maybe multiple lifts over a period of time on a project.

This then turns the rigging engineer loose to spend more time doing what-ifs than just grinding away on pages and pages of calculations. I'll give you a picture of some of the video screens that we're showing on our lift program. We bring a 3D CAD design models into this ALPS program, and with the various design vessels or heavy lifts that have to be moved and then in the program we've loaded it to date with about 16 cranes that we typically use on our construction projects. The databases have all the crane load tables included and all the information needed to select the proper booms, the proper riggings spreader bars, lifting beams, shackles, whatever that's needed to make the connections to the load and from there we're able to run and actually simulate the construction operations. We can even build temporary construction facilities that may be in the way of making a certain lift. Temporary facilities that will eventually disappear. They won't end up being part of the permanent structure, but they are real at the time the lift is being made.

I'm not going to spend a lot of time discussing this but what I'm trying to do is just give you an example. This is another shot of it with a split screen showing different views of the lift. As it goes through the cycle of making the lift, we can bring up windows that identify if any of the components are being stressed beyond safe lifting factors. One of the reasons that we spend time developing programs like ALPS and this kind of goes into I guess you'd say fill in the gaps of some of the earlier discussions. Automation tools to us are tools that should be looked at in assisting our construction people to do a better job, to become more productive on projects, help them become more productive.

Another example here we call Construction CAE. Again what we do is bring a 3D CAD design model into a scheduling program where we are able to link the 3D CAD design model with commercially available schedule programs like PrimaVera. On a split screen on the computer, we are able to build the project piece by piece just as you would in the old days where you had the plastic physical models, but here, we build it on the computer and at the same time as we are building it piece by piece, it automatically develops a schedule right there on the screen. Then we can play that back and go through a variety of what if scenarios to come up with an optimum sequence of construction. Again, this is a tool that helps us and helps our people at the job sites minimize construction time, minimize costs and of course become more productive on the job site.

Ken Goodwin, NIST: How does that differ from what's being built by Jacobus?

Clay Claassen, Bechtel: Jacobus has essentially acquired a program from us called Walkthrough. The Walkthrough program is a passive program where they can go into a 3D CAD model. They can move things around, they can walk through the program, look at it from various viewpoints; but they can't really have it directly interface with a schedule. They can't pull it apart into pieces, the model, to any great degree to actual construction elements to build a facility in the computer. So CCAE goes beyond Walkthrough so that you have a direct link between the schedule and the 3-D model.

So these are two programs that we have recently finished and from these we are spinning into an effort that we have been playing around with for close to a year now that we're calling fused reality. This is a consortium effort that has been pulled together. There is a variety of companies that have showed interest along the lines of seeing what we can do getting beyond just working with 3D CAD models represented on a 2D computer screen. We feel there are advantages to actually immerse yourself into that 3D model instead of looking at it from the outside. Now, your discussions earlier regarding the ATP program and the concern that the construction industry really hasn't tried to take advantage or get into accessing the matching funding for the ATP program. Well, we did with this consortium. We were fortunate enough to have a variety of companies;

in fact several of them are right here in this room to put together a program to seek an ATP proposal last year. We went the general competition route and didn't get very far. So the construction industry is seeking ATP funding, although we haven't had much success to date. Caterpillar was part of this and, in fact, this is still in the mill even though we missed this opportunity of the ATP program we are still seeking funding from other sources.

Another, and Perceptronics here, Gershon Weltman has been a big part of this, and another element that has been absolutely vital to what we think is an appropriate approach to ideas like this, is operating engineers, Local 3 in California, the ultimate users for a program like this. What we're attempting to do here with this program is to combine the attributes of virtual reality technology with the physical world. One thing about construction people is that we are visually oriented people. The more we can get abstract information moving towards representation in a visual manner the more effective we can be in using that information to increase productivity on projects.

So this particular approach is taking the 3D model, putting it into a virtual environment, so that the individual is immersed into that environment, but at the same time, which is similar to the heads-up displays that were discussed earlier, be able to see the physical world and actually interact with the physical world. It's not just a passive type visualization system. It's a proactive one.

What we're attempting to do with a program like this is to accomplish several things. One, initially, is to produce a means to enhance our ability to train construction equipment operators. We're going to take the ALPS program that we developed for construction cranes. We developed that program in an open system manner where we can load data regarding other pieces of equipment such as dozers and so forth, earth moving equipment, not just cranes, but be able to bring that environment to a new potential equipment operator where he can sit down at a station where he has actual controls sitting in a cab of a piece of equipment, but yet he's immersed in the construction environment. Our thought is that this will steepen the ramp-up for the individual in learning how to use a piece of equipment. On cranes, for example, on some of the large cranes, you're talking a piece of equipment that is worth a few million dollars. One of the risks is to stick new operators on an expensive complex piece of machinery before he's had a chance to get a little bit of a feel of that equipment -- you're running some significant risks of damage to the equipment; he's reluctant to really push the limit as far as learning because he doesn't want to damage the equipment either.

The other aspect is working with local operating engineers in California. They have a large training facility near Sacramento, Rancho Marietta, where they have a variety of earthmoving and cranes and so forth where they train their operators for service in California, Utah, Nevada and Hawaii. The best time to do the training of actually operating the equipment is during the summer months when it's relatively dry, the ground is in good shape as far as moving earth around. Of course, that coincides with the best working months, too. During the winter when a lot of operators are not working, and especially this winter because we had a lot of rain, more than we bargained for, it was hard to use the training facility like that because of the wet conditions.

With a program like this, the operators can ramp up quickly, learn the initial feel of the equipment, learn how to operate it, before they actually get onto the actual equipment itself. Then, beyond the equipment training, we see this as a tool where operators can actually rehearse complex operations on the job site. Over the years, I've talked to many crane operators on projects that I've been on where they are approaching a date for making a lift on something like a 300-ton generator worth about $10 million, that one piece of equipment. These guys have a few sleepless nights before they make that lift. They don't have an opportunity to rehearse. They have one chance to make that lift. That lift has to be done right. With a program like this, they can closely simulate that lift and rehearse the lift many times before the actual date of the real lift. Beyond that, taking a program like this and having it become a tool for remote control of equipment. There's more and more work that's occurring on hazardous waste sites, radioactive cleanup on many of the national lab sites. Here, you can have the same set up where the operator is using the controls. He's seeing the virtual environment of the actual equipment he's operating, what the equipment is actually doing, superimposed on what it should be doing, the design, and can control that equipment while sitting in the safe environment, not having to suit up with breathing apparatus and clothing to protect himself in a hazardous environment.

So these are all applications that we feel a program like this can fit. I might just say a couple of things on some of the earlier things that have come up. It was interesting watching some of the videos, in particular the Japanese building construction, etc. There's kind of a contrast of the driving forces here in the U.S. towards automation and robotics versus what we see in countries like Japan. The driving force behind the robotic applications in Japan is primarily due to a shortage of labor. The population to a great extent is not interested in going into the construction field and the Japanese aren't too interested in importing construction workers.

In the U.S., we have a different situation. It's our view that the U.S. labor force is really one of the most productive in the world. Where the failings have occurred is not in the labor force but in management's ability to utilize that labor force. Where we feel automation and robotics can play a big role in the U.S. is to help management do a better job to furnish information, materials, give craftsmen the right kind of tools and equipment to do the job properly.

The Construction Industry Institute, you may have heard of that, CII, in Austin, Texas, has done some studies a few years back on construction sites, mostly industrial construction sites, and they found that 30-40% of a typical craftsman's time is lost time because the craftsman, number one, does not have information he needs, design information on hand to do his work; he doesn't have the proper tools. He's either waiting or trying to find materials that he needs to do the job. So, we feel where we can make the biggest gains in improvement of construction productivity is to take that 30-40% and significantly reduce that lost time. We feel that automation and robotics can give us the kind of tools that will allow that to happen.

For the approach to best utilize automation and robotics, we feel that the effort should be more along the lines of identifying existing and emerging technologies and doing a better job of integrating those technologies, putting them together in a manner that they become useful to the construction industry, rather than at this stage in new blue sky R&D. We feel the construction industry can make significant advances by taking advantage of technologies that are already available. This is one concern that I have regarding the ATP program, because it is my understanding that one of the criteria for award of the ATP program is that the technology has to be new technology. It can't be an existing technology. I think the focus is wrong on the ATP program as far as how it can best service the U.S. construction industry.

In the U.S., of course, our economy is such where we are focused on the annual statement, and therefore companies such as Bechtel and others in the U.S. have to produce quick deliverables if we are going to spend any time on new technologies. We don't have the opportunities to look out two and three and five years ahead. We have to spend time on things that are going to produce results to the bottom line within a year or less. Therefore, the ATP approach is a little bit of a disconnect there. Our view is that if NIST or the Federal government can help the U.S. industry it is to somehow come up with programs that help our industry to implement beta test and integrate technologies that are just now emerging.

Jim Albus, NIST: Where are you going with that ATP proposal? Are you going to try it again?

Clay Claassen, Bechtel: We are not sure. We're looking at various other government agencies as far as funding. In fact we have some interesting prospects right now with the state of Utah working through the University of Utah and the university system. Their Department of Education is showing some interest in providing some matching funding to set up some prototype testing in development of a program like this in their university system. Then also the challenge grant programs with the Federal Department of Education looks like there's some opportunities on programs that they have set up to work with disadvantaged and minority secondary high schools. In California, again working with Local 3 operating engineers, in the city of Oakland, there's a high school that we've been over the years working very closely with (Oakland Tech) where we might be able to access some funding to set up a testing program to help prescreen highschool graduates that are showing an interest in getting into the construction industry and do operating construction equipment. So those look like some promising opportunities we're pursuing. We're looking at a variety of approaches. We haven't given up.

1.12 Intelligent Control of Mining Equipment and Systems: Lessons for Construction Automation

Robert H. King
Colorado School of Mines

The international mining industry is highly competitive, forcing managers to take dramatic steps. Some of these steps are: closing mines, reducing work forces, negotiating wage agreements, and purchasing the most productive equipment. Managers are exhausting these traditional avenues and are looking for new solutions such as advanced technology.

For example, some operators achieve productivity gains through modern equipment purchase. The new equipment is very expensive and requires maximum utilization to make it cost effective. However, mine workers do not obtain maximum efficiency because the adverse and hazardous mine environment impedes human performance. The evolution of mining machines has reached the stage where, in an attempt to improve productivity, machines have become increasingly expensive and complex, and pose excessive demands on the already highly stressed operators. Often, the potential capacity of a machine outstrips the manipulative skills of the person operating it. For example, underground coal continuous miners are only utilized 17% of the shift. Also, the efficient use of large, complex machines calls for levels of precision which many times are beyond the capability of even highly trained miners. In addition, these expensive machines should not sit idle while miners do other activities.

Some mining companies, government research laboratories, and universities began experimenting with sensor-based, closed-loop control to provide aids to increase precision and productivity. Automation has been used in mining for many years in process control and material handling, where stationary structures like conveyors, pumps, hoists are controlled by computers or PLCs. Recent work in robotics goes beyond automation to control mobile, multi-functional equipment in the ore and coal extraction activities in the mines. These recent efforts in mining robotics are the topics of this paper. Control of processing plants and stationary materials handling equipment will not be discussed.

Mining robotics is a controversial topic. Some miners see robotics as a threat to their jobs. Others see it as a change that will remove the art and romance from mining. Others believe robotics will never progress to the point of cost effective application in the rough mining environment, and some predict it is the inevitable future of mining. Many of these different opinions stem from different perceptions of a robot. When thinking of a mining robot, people visualize a wide range of forms from a human mimic like Asimov's R. Daneel Olivaw, to the Star Wars R2D2, to a machine that looks similar to a present mining machine but is computer controlled. The latter is more correct.

Robotics technology is applicable to surface and underground, but underground mining usually is less productive and more hazardous (when done by people) and, as a result, will probably have a higher applications opportunity. It is expensive to maintain an artificial environment in an underground mine that is conducive to optimal work performance by people. By its nature, underground mining can be hot or humid, in addition, the equipment produces dust, noise, fumes, and other hazards. Explosive or toxic gases and the constant danger of rock falls add to the increasing list of health and safety concerns that have initiated volumes of federal and state regulations for maintaining safe work places for humans in underground mines.

Safety and costs are related. Safety regulations in most countries cause tremendous capital and operating expenditures that prevent many mineral deposits from being mined profitably. For example, in both underground coal and metal mines in the US, miners excavate many more entries or drifts than necessary to produce and remove the ore or coal in order to provide a safe environment for humans. These difficulties will increase as mines deplete near surface reserves that have the best working conditions.

Mines can gain great advantage by developing equipment and associated mining systems which ease the burden of the operators by removing them, as far as possible, from the hazardous and stressful environments and provide the opportunity for greater productivity. Miners can be removed from the hazardous environment by teleoperation. Intelligent control is not necessary. However, teleoperated equipment moves much slower than manned machines. Teleoperators require computer assist to obtain cost effective productivity from mining equipment. The computer assist must incorporate intelligent control to react appropriately to the unpredictable and dynamic geologic changes in the mining environment. Teleoperation with intelligent control based operator aids is called telerobotics in this paper.

This paper surveys a wide range of telerobotics projects recently completed and currently underway internationally. However, due to publication length restrictions, it is not comprehensive. The projects described herein achieve or promise benefits of improved costs and safety which are all closely related. Productivity can be enhanced with multiple machines per operator, continuous operation, and machine availability. Costs can be reduced by better environmental control, less machine damage, higher product quality, optimal use of electrical power, and reduced need for ground control. Safety is improved by reducing exposure to hazards like ground/roof falls, machinery, and respirable dust.

Underground Hardrock Mining Systems and Machines

Some of the more interesting work in automation today is taking place in Finland. The Finnish intelligent mine concept encompasses a mine-wide monitoring system, high speed bi-directional communications, computerized information management, and automated and teleoperated equipment. Through utilization of these technologies, total economic improvements were forecast. Particularly, increases in effective working time, quality, and selectivity were targeted. Some of the projects focus on robotics, like automation and teleoperation of charging and shotcreting, an automated trolley powered truck, and unmanned Load-haul-dump (LHD) units.

Significant effort has gone into the automation of wall-drilling in mines. New rock drills are being developed that contain a microprocessor; a control console; angle transducers at boom joints; linear transducers for extension, feed, and crowd; hydraulic sensors; and electro-hydraulic valves. The drills operate in either automatic, manipulator, or manual mode. In automatic mode, a drill pattern in the computer defines the position, direction, and depth of holes in relation to the tunnel axis. The machine drills the round automatically and allows the human operator to complete other tasks, such as setting up another drill.

The operator can modify and store drill patterns with a portable computer to avoid collaring in holes left from the previous round. The sequence of events begins by inputting a reference such as the relation between the tunnel axis and a fixed laser beam. Then the drill is manually trammed to the face and a drill rod is aligned with the laser. The operator presses the navigate button and the jumbo drills the round if it is physically able to reach all the hole positions. A video display shows the entire pattern and shows which holes have been drilled. The video display graphs penetration rates for each drill to help the operator determine when to change bits and whether strata has changed. The display also shows boom positions relative to the reference axis. In manipulator mode, the computer actuates the boom and drill movements that are manually commanded. The movements are therefore more efficient and accurate in response to "joy sticks" than in the manual mode. Display features are also active in manipulator mode.

Computerized jumbos are expensive, and mine operators claim they do not replace the human operator for long enough periods to realize significant labor savings.

A lot of work is also underway in load-haul-dump guidance systems. In one test, an LHD trammed automatically between the dumping and loading points with a TV camera. This allowed the operator (a remote supervisor) to load or dump another machine while the automatic tramming activity is underway.

In another test, the operator drove the LHD using a TV and monitor placed inside a cab with the windows covered. Experiments are also being conducted with painted-line following techniques similar to those used by automated guided vehicles in factories and warehouses. Painted lines can be repaired and altered quickly and inexpensively, so they might be applicable to mine environments. Researchers in Sweden have painted a 10 cm wide line on the back of a haulage drift and used CCD cameras to locate the line. This system could detect 10mm deviations from the path.

The results of this research led to several LHD units being supervised by one operator on the surface at the LKAB mines in Sweden. The operator loads and dumps the units with teleoperation, and the units tram between loading and dumping areas automatically. A control wire embedded in the roadway is sensed by the LHD and used to locate its position along a predetermined path. Video image transmission to remote monitors are used to control loading. These tests showed that an operator can control at least three LHD's from a surface control room. The LHD's can tram at 80-90% of the average speed of manually driven units. At the Swedish Zinkgruvan mine remote control has been used for several years, and operators are now being moved further away from the units by mounting TV cameras and transmitting the video to two monitors in a remote cabin. The operator uses the forward looking camera to load and dump the unit.

In another LHD teleoperation system, video images from four, fore- and aft-looking cameras are transmitted over a 1.5 Ghz radio signal to receivers in the operating area and from there via telephone cable to a control room. The control room can be located on the surface of the mine or near, but out of sight of, the LHD's. The control room has a main computer for reception and analysis of machine monitoring data. Both health and production are monitored. The room contains four monitors, one for alarms, the second for a map of the area with LHD location with a split screen for vehicle health, the third for production analysis data, and the last for the video images from the onboard cameras. The unit trams via buried wire, and the video images are used for loading.

Another approach being investigated is to use an automatic steering system for articulated vehicles that doesn't require installation of targets, paint stripes, or guide wires. Because of the hazards of maintaining these structures, they used ultrasonic rangers mounted on the vehicle to provide distance to the ribs and in-drift obstacles. An intelligent control for machine guidance was initiated using the real-time-control-system (RCS) architecture. This guidance system could be applied to several machines in underground metal and coal mines, and particularly on the electric trucks in use at the Zinkgruvan mine.

In a similar teleoperation effort, a video camera was installed on an LHD and the image was transmitted 23m to a remote operator in the Noranda Lyon Lake Mine. The purpose was to help the operator to load the bucket fully when operating by remote control in a production draw point below a bulk mining stope. This was an important study because for many years, the phases of robotic development in mining will require the use of supervision. Supervisors might need video images to properly control robotic equipment in contingency situations. Video transmission using radio waves (without tethers and leaky feeders) is difficult. Thus far it has only been practical to transmit 100m. Digital video data has been successfully accomplished from a camera with 510 X 492 pixel images with a transmitter providing one Watt of video modulated radio frequency at 439.25

MHz powered by 12 v dc from the LHD circuit. The LHD operator used a 4-inch monitor provided with the system to successfully load the LHD bucket.

Mount Isa Mines and the Colorado School of Mines developed a teleoperated LHD that removed ore from a high grade zone with poor ground conditions. The teleoperated LHD was slower than manually driven units, but its continuous operation resulted in adequate end-of-shift production.

Continuous Underground Coal Mining Systems and Machines

The U. S. Bureau of Mines initiated the Reduced Exposure Mining System (REMS) based on studies that revealed 106 of 268 deaths and 21,552 of 54,642 severe injuries in underground mining from 1986 to 1992 involved equipment at the working face. In addition to the immeasurable loss and distress to families caused by these deaths and injuries, each fatality was estimated to cost over $1 million and each lost-time injury over $9,000. The objective of REMS is to remove workers from the hazardous face area. The REMS systems includes a continuous mining machine, a continuous haulage system, ore shuttle cars, and a roof bolting machine.

This systematic program includes research in the basic machine electrical, mechanical, and hydraulic components; sensors, algorithms and languages for intelligent closed loop control; obstacle detection and guidance sensors and algorithms; geosensing sensors and algorithms; machine health sensors and knowledge based systems; and path planning algorithms. Bureau personnel are carrying out and demonstrating their results on a modified underground coal continuous mining machine and haulage systems fitted with electrically actuated controls in their Pittsburgh mining equipment test facility and on a modified roof bolting machine at the Spokane facility. Initial research products were further tested in the Marrowbone Development Corporation underground coal mine in West Virginia for two years where non-line-of-sight teleoperation of the continuous miner and computer control of the cutting cycle were demonstrated. Additional laboratory work is currently underway in preparation for more field trials of the complete system in late 1997.

Suboleski, working at the Colorado School of Mines, developed a closed loop control system for all mining machine functions except tramming, using sensor output from rotary variable differential transformers and hydraulic pressure, temperature, and flow transducers. He achieved on/off closed loop control for shearing up/down, stab jack up/down, and conveyor swing left/right based on position of each component when operating in free space and cutting coalcrete. The tram fast/slow forward/reverse and pivot right/left were controlled in an open loop (time clock limited) mode. The control safety relay and the pump, gathering head/conveyor, and cutter motors were operated in latched on/off mode. He established set points in degrees of movement reported by the resolvers and evaluated errors caused by lag times in both the hydraulic and electrical systems. The system operated accurately in free space and when subjected to the vibration and stress of cutting coalcrete. Sammarco described initial efforts to fail safe the control with checks on microprocessor power and software execution, and recommended additional verification of sensors and machine during startup.

In an effort to extend closed loop control to tramming, experiments have been conducted with on-board machine attitude and location sensors including a gyroscope for entry center-line control (yaw), flux gate compasses for redundant heading data referenced to magnetic north, and clinometers for gravity referenced pitch and roll. The objective of the on-board system is to provide attitude and location within a cut. The on-board data is fused with laser-based angular positioning system for long range guidance. The gyro has the following characteristics:

- drifts 9.73 degrees/hr in Pittsburgh,
- cumulative errors,
- moving parts that will require maintenance,
- very expensive,
- needs a 5-10 minute warm-up period,
- requires special power sources, signal conversion, and control, and
- provides +\- 0.02 degree heading changes within milliseconds.

For comparison, it has been determined that local magnetic fields affect the flux gate compass and it was not able to keep up with a machine pivoting at 3.3 degrees/second, but it doesn't drift, its errors don't accumulate, it has no moving parts, it doesn't require warm-up, and it is inexpensive. The present flux gate requires the machine to be stopped for 2s to accommodate the present 2s averaging window; however, it is believed that modifications might be possible.

Another development involves a laser-based angular positioning system for precise longer range navigation guidance of the continuous miner in the face area. The positioning system reference is a mobile control structure, patterned after a mobile roof support that will follow the continuous miner along an entry. Either surveyors or a long range automatic total station will determine the precise coordinates of the mobile control structure after it is set at the face. During the excavation of each cut, the continuous miner will locate itself relative to the mobile control structure with a laser scanner mounted on the mobile control structure seeking retroreflective targets on the miner. Multiple scanners that sweep 90 degrees each and multiple targets reduce obstruction problems and provide redundancy.

Anderson's algorithms use two geometry's to determine position and attitude, one where two or more laser photodetectors sense the angular position of two or more targets on the machine and the other where one photodetector senses three or more targets. Anderson is developing a fusion algorithm that assigns confidence weights to each angle measured based on the knowledge that certain orientations affect measurement reliability.

The present sensor of choice is a modified Modular Azimuth and Position System (MAPS). The system uses three orthogonal laser gyroscopes and accelerometer data to calculate machine position and orientation. It does not require off-board sensors or targets.

The continuous coal miner used only position sensors for controlling the cutting horizon; as a result, frequent contingencies arise because seam height varies dramatically in some mines. The key to handling the dynamic underground environment is to apply intelligent control based on sensor information that accurately describes the dynamic and unpredictable environment. Work is also underway to study waveforms generated by accelerometers mounted on the machine and on the coal to develop algorithms which will automatically discriminate between vibrations resulting from cutting coal and rock. Natural gamma radiation had also been used successfully for cutting horizon definition.

Infrared imaging is another technique under investigation because it discriminates between coal cutting and rock cutting by producing images of the higher temperature areas that result when cutting rock. However, this technique requires compute intensive video image processing.

Underground coal mining companies have found that interface detection is a good operator aid that provides considerable cost savings in preparation costs, material handling costs, and equipment wear. Consequently several researchers have developed robust, precise sensors for operator aids on continuous miners. These sensors have been successfully applied to longwall mining equipment.

Intelligent robotic control algorithms are needed to reliably and efficiently operate in the dynamic mining environment. That is, the continuous miner will be able to alter its cutting plan if sensors report deviations from the conditions and events used to generate initial plans. Bureau of Mines (REMS) researchers developed three software modules for this objective. The navigational goal scheduler will plan the sequence of machine actions and positions necessary to complete a cut, and represent them as a series of goals. An action planner will plan the actions necessary to progress from one goal to another. The contingency goal scheduler will allow operations to continue when the miner can't reach a planned goal. It will attempt to discover the problem and plan an alternative goal. To speed the application of intelligent control to mining, the Bureau contracted the National Institute of Standards and Technology to transfer their standard architecture for intelligent control of manufacturing robotic work cells and the space station robot to the autonomous continuous miner program. The result has been the implementation of very complex code in a modular design that is flexible and easy to understand, modify, and maintain. Each module occupies a position in a hierarchical, multi-level task tree. In one heartbeat, all control modules are processed including all sensor inputs and variables. As each module receives a command from the next higher level, or superior, it checks its relevant data and issues a command to one of its subordinates. The superior waits for a done or error signal before executing another command. The code is implemented in C.

The REMS computer system includes machine controllers, operator interfaces, machine simulators and graphic visualization displays. All are PC's running MS-DOS except the UNIX graphics workstation visualization system. The operator interfaces and visualization system are housed in a portable underground control center.

The autonomous continuous miner will cost much more than present machines. Therefore it must be very reliable to be cost effective. High reliability also reduces maintenance personnel exposure to face hazards. Consequently, the Colorado School of Mines developed an expert system prototype to interrogate the various hydraulic sensors and report on machine health. The system diagnoses hydraulic problems based on sensor and user input. It will explain how it reached conclusions, and provide recommendations for repair. This can be done using a hierarchy of rules to represent the knowledge of hydraulic diagnostic experts and backward chaining to search through the knowledge base to diagnose the condition of the hydraulic system. The present system has been implemented with the Rulemaster expert system generator. This work has been extended to the electrical system, and eventually machine health systems will cover all the continuous miner components. A prototype expert system for interactive troubleshooting and training of personnel for electrical system fault diagnosis with the Level 5 expert system tool has been developed. These systems are now being merged and research is being extended, especially in electrical motor diagnostics, into an overall diagnostic system that can be applied to processing plants as well as continuous miners.

Similar relationships have been studied using an instrumented roof bolting machine. The intention in this case is to determine the optimal type and installation of coal mine roof bolts which ultimately will improve the intelligence of autonomous roof bolting machines. This system will replace the feel and expertise of the expert roof bolter operator to adjust standard bolting patterns to achieve the best support when rock mass properties change. A real-time measurement and display system has been built that calculates instantaneous specific energy at the current bit position in 1-inch intervals and logs each hole drilled on an experimental machine at the Bureau of Mines Spokane Research Center. Sensors on this machine measure torque, thrust, penetration rate, and rotation rate. The system aids the roof bolter operator to locate voids, inclusions, and changes in strata. The sensors report data to an on board computer in a permissible enclosure. Some data (specific energy versus bit and void position) can be downloaded to a removable semiconductor memory device for additional processing on an off board "fresh air" PC that is also used for software development. This system can be extended to closed loop automatic control by adding servo valves to the hydraulic control circuit. The full-control bolting system which reports anchorage strength and installation torque of each bolt and matches the bolt installation procedure to the existing geologic conditions is under development. Using this combination, the system will identify roof properties during drilling and select and carry out the appropriate roof bolt type and installation procedure to provide optimal support. Vibration sensors and processing algorithms will be added along with an expert system to assess machine health.

The Deserado underground coal mine installed a computer monitoring and control system for their conveyor belt network. The system increased the availability of conveyors to over 90%. The average for non-computer controlled belt networks is below 70%. The system allowed remote starting from the surface where a central operator was on duty continuously. Most stoppages could be identified by location and cause, facilitating central operator to quickly dispatch the appropriate persons, tools, and parts to the necessary location.

Multiple machines with video image understanding require a high-bandwidth communication system. Obviously such a system can be applied to monitoring and management information systems.

Longwall Underground Coal Mining Systems

Underground coal mining companies are vigorously pursuing longwall automation to improve productivity and reduce costs related to strict respirable dust regulations. Consolidation Coal Company has conducted efforts from 1985 to 1991 to develop an automated longwall system. A master microprocessor coordinates the activities of microprocessors that control the shearer, control the shields, and provide data to the surface. The result has been enhanced safety, increased productivity, improved product quality, increased equipment availability and support automation. Since 1980, 86 longwalls have been introduced in the US, including 33 with electro-hydraulic control, and 10 with shearer initiation.

A fully automated longwall has been implemented at the Consolidation Coal Company's Blacksville No. 2 Mine. This has been in production since 1991. Semi-autonomous double-ranging arm shearer and shearer-initiated automatic advance of shields capabilities were accomplished. Component reliability was key to successful implementation. The best technology in manually controlled equipment, such as 650 ton 2-leg "lemniscaateshields", formed the basis for the system. Then, shields were required to successfully complete a rigorous battery of structural tests and electro-hydraulic controls were similarly required to pass environmental tests incorporated in purchasing specifications. In addition, a small scale surface trial of the components assembled as a system was completed prior to underground implementation. Consolidation Coal Company's premise was that several earlier attempts at longwall automation failed due to low reliability, not due the concepts of automation. Computer control was added to this reliable system by installing a surface data station, a headgate processor and a shield central station. The shearer communicates its speed, direction of travel, and position to the headgate computer via inductive radio communications over the shearer trailing cable. Sensors for face end, arm position, cog counting, interface detection, and cowl position provide information to an onboard microprocessor that autonomously controls the shearer hydraulics and tram electronics. Shearer position information is communicated to the shield central station so shields are automatically advanced in groups of 2 or 3 immediately after the shearer passes. Numerous benefits have been realized which quickly recovered the added expense to install and maintain the control system. The benefits were: longwall availability increased to over 95%, productivity improved with peak production of 7700 raw tons/shift (constrained by haulage), reduced supply costs, reduced run-of-mine reject, reduced dust exposure, better manpower utilization, improved management communication and control, increased recovery, improved ground control, reduced maintenance and operating costs, improved troubleshooting, and early warning of some equipment failures. As a result of these many benefits, two more automated longwall systems are planned for other Consolidation Coal Company mines.

In Germany, efforts have been undertaken with the objective of achieving a partially automated long wall mine. They have automated roof support movement and fore poles for plough and shearer faces. The automated supports control the plough web through defining the advance. Optical sensors provide reflectance data to differentiate between coal and rock for intelligent control of plough level. Shearer level (or horizon control) relies on merged data from optical sensors, sound and vibration, and a sensitized pick. Empirical data knowledge bases and learning cuts are used to interpret real-time information.

Intelligent control is supplemented with the INTEK expert system that identifies early damage and aids in diagnostics of shearing machines. The Germans did not find adequate off-the-shelf sensors to support their intelligent control needs in the difficult and unique mining environment, so several sensors are under development. Position sensor development was based on gravity combined with a gyroscope. Obstacle detection was based on merged data from ultrasound and optical sensors. Vibration data analysis was used for early damage detection. An image processing system was being developed to identify protruding loads on conveyors and transport vehicles. An electric motor drive sensor was under development that evaluates operational characteristics and provides additional early damage detection. Furthermore a support manipulator, a mobile material manipulator, and a master slave manipulator were being developed for materials handling activities.

Highwall Coal Mining Systems

CSM has teleoperated a low profile continuous miner and haulage system to extract coal from strip mine highwalls at the Bureau of Mines Pittsburgh Research Center mining equipment test facility. The system will mine without exposing people to the hazards of the working face, since the operator will remain in a supervisors' station on the highwall bench while the miner and haulage system extend up to 1000m into the untapped highwall reserves. The teleoperated miner will use a laser beam as a guidance reference. A tether carries operator commands, audio/video signals and sensory data between two microcomputers housed in the supervisory station and the machine. The Bureau researchers modified a low profile machine that the manufacturer equipped with tethered remote control. They added two color video systems, microcomputer and communications hardware, explosion proof housings for the new electronics, and a suite of sensors to measure machine health, attitude and position. The miner can load coal into a variety of haulage systems, but the researchers chose the multiple-unit continuous haulage system previously developed by a Bureau contractor . Highwall systems are also under development by BHP in Australia and Consol in the USA. Teleoperated high-wall miners have been adopted by several mining companies that have advanced the technology by using ring laser gyros and back-scatter gamma sensors.

Surface And Open Pit Mining Systems and Machines

The Caterpillar Vital Information Management System (VIMS) acquires, stores, displays, communicates, and analyzes information from sensors on mobile mining equipment. VIMS is a PC-based system containing a main control module that communicates with other controls on the machine (such as the electronic engine or transmission controls), or with sensors connected via one or more interface modules. The main module stores and analyzes data and communicates to the operator and/or a remote station via a radio dispatch system. The VIMS has reduced costs and increased productivity of manually operated mobile equipment and is applicable to robotic systems. For example, VIMS reduced the downtime to repair a torque converter lockup clutch solenoid on a large haul truck by 83% and increased time available for production by 3.3 hours by reducing the time and effort required to diagnose the problem. In another instance, VIMS saved over 8 hours in downtime and 5 hours in repair time plus reduced parts costs by detecting a slipping alternator belt before the belt broke.

Work is underway on algorithms that will make computerized rock drills more intelligent. Sensors on surface mine drills have been used to monitor rotary speed, torque, thrust, air flushing pressure, and instantaneous penetration rate with a microprocessor on a surface blasthole rig. Relationships have been developed between the changes in these data and rock mass properties. This work will allow drills to characterize the rock mass they are drilling. As a result, the control system can recognize and respond to rock mass changes automatically and optimize penetration rates while minimizing wear and maintenance on drilling equipment.

Tunneling

ZED, CAP, and Lasernet systems are presently available for guidance of tunnel boring machines (TBMs) and road headers as well as continuous miners. Road headers also have automatic profile control. The ZED system uses an off-board laser that intersects targets on the TBM to obtain yaw. Guidance sensors can be merged with overall information systems for construction to provide the basis for future intelligent control systems.

Summary and Conclusions

The definition for robotics, "robotics is the intelligent connection between perception and action," implies a link between artificial intelligence and robotics, and that robotics is more than a single machine. It is a technology from which mining engineers and researchers can borrow pieces to gain advantages for the mining industry. I have briefly summarized mining automation research which involved the development of aids for machine operators, the provision of information for managers, and the development of algorithms to predict machine failures. None of these projects involve what could truly be called a mining robot, but all have benefits for the industry. The USBM work on the autonomous continuous mining system is the closest project studied to an intelligent robot.

The robot definition includes perception, the ability to understand the world around the robot. Perception requires a suite of sensors whose fused data accurately describe the environment around the robot. Artificial intelligence based algorithms are used to analyze the data and to build models and paths for robot control. This part of the definition is very important for mining since perception of the highly variable, complex mining environment is the key to the successful application. However, the cost to reach automatic perception may be so high that it is inappropriate for most, but not all, mining needs. Automatic perception for mining is difficult because mining tasks are not a series of cyclic motions readily accomplished by factory floor mechanisms. Mining takes place in the geological environment where conditions are highly variable and unpredictable. As a result, completely autonomous mining systems must have substantial cognitive abilities to recognize and deal with these unpredictable variations. Although robust autonomous vehicles have been developed that will withstand harsh outdoor environments and cope with a dynamic environment, they are very costly.

Robotics technology costs are affected by the following mining environmental issues:

1. Some mining equipment (like mobile haulage vehicles) can navigate from a map. They do not need to explore.
2. Mining engineers can modify the layout to reduce the navigation and obstacle detection problems.
3. The mining environment is harsher in some respects than any that autonomous vehicle research programs have encountered.
4. Mining equipment must operate faster and more precisely than most of the present autonomous vehicles.
5. Mining equipment must operate reliably over long periods of time.
6. Mining machines must have better onboard machine health monitoring and diagnostics.
7. Excavation and drilling equipment require geo-sensing.
8. Some of the autonomous vehicle program technologies are not cost effective for mining. For example, the software development and compute power for robust image processing is not cost effective in the dusty mine environment.

Because of these special circumstances, many robotics technologies can be applied in a cost effective manner to improve productivity, costs, and safety in mining.

Research efforts in the future will no doubt be focused in four areas. These include:

1 Computer representations of mining specific knowledge in areas like layout and planning, machine capabilities, mine geometry, machine interactions, and machine conditions
2 Cost-effective sensors that will perceive and withstand the special mining environment
3 Analysis (using pattern recognition algorithms, for example), merging, and reasoning concerning mining specific sensor data and knowledge to develop algorithms to intelligently control machines
4 New mining methods or new approaches to traditional methods through removal of constraints imposed by the necessity of human operators.

1.13 Automation from an Industry Viewpoint

Kenneth F. Reinschmidt
Stone & Webster

[Editor's Note: The first few minutes of this talk were not captured on tape due to technical difficulties]

The videotape shows a job that Stone & Webster performed for the Tennessee Valley Authority. This is an environmental retrofit (flue gas desulfurizers) to an existing power plant. The computer system COMANDS was used to build a four-dimensional construction sequence model. In this project, the owner allowed only twelve weeks for the plant outage. To meet this requirement, we had to go through a number of studies of alternate construction sequences to determine how we were going to do this job in twelve weeks. We put the construction plan together visually as part of the bid package and we showed it to the client, to prove that we could do it in twelve weeks. This demonstration won the job for Stone & Webster against the competition.

This job was similar to our work with a number of automotive and other kinds of manufacturers in that time is a high priority issue. Time reduction or some other high priority objective must be identified in order to see where to apply new technology. That is to say, cost is important, but (as others have discussed), how do you recover the cost of developing new technology if you have to underbid the competition to get a project?

If cost is the sole factor, introducing technology in any area is difficult. I believe that relatively little new technology has been introduced which did the same thing as its competitor, but at a lower cost. Usually it does something different, something better, that adds value to the user. Then, when it reaches volume production, the cost comes down. For example, when Intel introduced the P6 it was not initially cheaper than the Pentium. They initially charged more for because it runs faster. After they make around two million of them, the price will come down. I think you have to find something other than cost to serve as the driver to develop new technology.

The COMANDS system is used in checking whether all the necessary materials and components are available on site at the time each construction work package is to be erected. Getting the right material to the right place at the right time is an essential part of construction as it is in manufacturing. As a matter of fact, a factory can be characterized as a way of organizing the environment and getting materials to the right place at the right time. Factories do that better than typical field construction projects. However, on a job we did recently, the construction people at the site reported that they were getting all of the material off the trucks and into the plant without going through multiple handling in laydown areas and warehouses. Ten years ago, I would have told you that the construction people would have been interested in how to find material in a laydown area. Now, the answer to that problem is to have no laydown area. That means you have to track equipment and you have to be able to look at how any delays will impact the schedule and develop workarounds dynamically. Here we use the 3D model to visualize what we are going to do, step by step, and then generate a schedule from it. That is, we are trying to get rid of arrow diagrams or precedence diagrams and build this project in a graphical representation and then extract the schedule from the visualization.

This allows us to simulate the construction in full three-dimensional geometry and to evaluate many more alternative schedules in a given time. In winning the job from the Tennessee Valley Authority, we had to look at many alternate construction schedules. To reduce the outage time, we had to do things in parallel instead of in sequence, and that raised a problem because the plant allowed only a 12 week outage and there wasn't physically enough access in the existing plant to do all the activities in parallel. We had to examine how to eliminate congestion problems in order to perform more work simultaneously. In that particular case, one solution that was developed (through the use of the three dimensional model) was to build a temporary platform, and put the cranes on this platform while allowing work to go on underneath. This sequence was simulated in time using the three dimensional model, which confirmed that the work could be completed in twelve weeks.

Part of our objective here is to reduce risks. Construction is one of the most risky businesses you can be in, and people don't want to accept other new and unidentified risk factors. However, by simulating the construction process, we can eliminate risk factors or we can see how to deal with them. That means, of course, that the people who build these schedules have to be experienced construction people, not engineers or designers or computer operators. And construction people have to use the system on the site.

This system has been used on our construction sites since 1987, and it essentially enables construction to drive the project. Engineering doesn't drive it. Engineering is essential, but construction drives the project. This tool puts construction in the driver's seat. That is perhaps not comfortable to the engineers, but it allows construction to assess the risks. Rather than producing rigid schedules that cannot possibly be achieved under actual conditions, the system provides the flexibility to revise those plans and schedules dynamically in the field.

So we create this virtual environment with the 4D model; from the beginning, time was always one of the most important factors. That, if we practice executing the project enough times, in a virtual environment, we will learn how to do it the best way. What we learn in practice is not how to do the work of the trades (because Stone & Webster is a union company we expect that the trades know how to do their business). The people who have to learn are the supervisors and the planners: they have to learn how to organize the work and they try different solutions in order to find the best one.

A virtual-reality system must be developed hand in hand with the construction people, the people who are going to have to use it. It's not a case of technologists pushing technology until the construction force is ready to accept it. We did find, however, that the construction force was very receptive to 3D modeling as soon as they saw it; it is obviously so much superior to ordinary engineering drawings for communication with the construction workforce.

What we are seeking ultimately is a way of organizing information. A factory can control its environment, and we seek to accomplish the same general objective on the construction site, but of course using different means. (The tape shown by Jim Albus on the Shimizu system shows one attempt to control the environment on a construction site.) Because we cannot control the environment on a construction site in the same way that it is controlled in a factory, we must try to get information about the construction site and know where everything is. Feedback of as-built information is very important.

The COMANDS system generates networks which are fed into Primavera to generate the critical paths. We have also found that the standard network paradigm is inadequate and we have been working with feedback dynamic models which allow consideration of such things as rework.

In a network model, there is no representation of feedback, no representation of rework, and no way to represent the impacts of rework. In a feedback dynamics model there is. One thing that a system dynamics representation shows is that the quality of work is very important, because lack of quality causes recycle and rework. Whether the rework is in construction or in engineering and design, rework impacts costs and schedules, and it is very difficult to see this ripple effect in the linear network model and very easy to see in a feedback model. As quality decreases and rework increases, the duration and the costs go up rapidly. The system dynamics model allows construction personnel to simulate and evaluate different methods for improving quality, such as more supervision, for cost effectiveness.

To summarize, I think we have to identify how automation is going to fit in the total pattern of what we do on construction sites. Working with a number of people in manufacturing — where designing their products is separate from designing the facilities that make their products — they are definitely concerned about integrating automation and we have learned a lot that can be carried over to construction.

In the automotive business we said: We can help you improve productivity and cut costs; but the automobile people replied: That's good, but does it get us the car faster? Certainly other things are important: they have to meet the weight requirements and they have to meet the cost requirements of the car. But their primary driver is getting the car faster because that is their competitive issue.

At the start of the presentation this morning, Dick Wright said that the national goals established for construction call for a 50% reduction in project delivery time. The Civil Engineering Research Foundation sent out some Delphi surveys to a number of people in construction internationally. One of the questions we asked: What do you think is the achievable reduction in project delivery time by the year 2005? The average of the responses was 23%, or about half of the national goal target. Yet, some automobile companies have reduced their product delivery time by 70%.

One of the additional questions was: How would this reduction be achieved? Of the total 23% reduction, use of site automation and robots contributed somewhat over 3%, so there isn't a lot of confidence that time reductions will come from the use of robotics. Increased use of offsite manufacturing contributed somewhat under 5% of that 23%. Use of Global Positioning Systems contributed another 2%.

My feeling from the Delphi survey is that the responses are not ambitious enough. Perhaps this is because the benefits of such improvements are not captured by the construction community. Constructors don't make any more money building projects faster unless the client provides a financial incentive out of the added value he gets from completing the project sooner.

The Delphi survey addressed many more specific issues regarding technology in construction, but the general conclusion I would draw from them is: If we are going to get the benefits of automation in construction, we have to combine advances in specific automation technology with changes in the overall design/construction process, and that isn't easy because of the fragmentation of the industry. But this is in fact how the aerospace, aircraft, and automotive industries have achieved cycle time and cost reductions. They did it not by one big thing or two big things but by many, many, many little things, all of which were focused on the overriding issue of product delivery cycle time reduction, product quality improvement, or some other definable objective that represents a competitive factor.

Milt Gore, Dupont: *I second your remark that new technologies have to create new things, new ways of doing things, to enable new things to be for them to take hold. Sometimes those new things really are time effective. I always think of the example of the hand-held calculator. Everybody wanted their own and the only thing it ever did was make addition and subtraction faster. When you say that 50% may not be ambitious enough, I think that was probably the case there: it was orders of magnitude faster and more accurate and combined with nominal cost.*

Ken Reinschmidt, Stone & Webster: I am sure that calculators are a lot faster than my slide rule, and they sure carry the decimal point a whole lot better.

Milt Gore, Dupont: *Slide rules actually work faster than abacuses at first. But using an abacus is a specialized skill. They made it universally possible and I guess the question is: "Is there really not, you know when everyone says time is probably the metric, that is the most affected but from a construction stand point, if you could do each job in* *half the time, couldn't you do twice as many jobs in a year and therefore improve your thruput and double the revenues?"*

Ken Reinschmidt, Stone & Webster: Well, we would certainly like to do twice as many jobs. But in order to do that we have to win them.

***Milt Gore, Dupont:** But being the company that can do it twice as fast would certainly win you some work.*

Ken Reinschmidt, Stone & Webster: If costs were held constant and you did the job in half the time as the competition then you would get the awards. But if the technology required to do the job in half the time costs more, you might not. That is determined in the market place. Certainly it cost Stone & Webster more to bid the TVA project than it normally would, because of all the computer modeling and alternative construction approaches evaluated. And this was at our risk; we could still have lost the job. We can't keep adding value for the clients if we don't keep our margins up, no matter how many jobs we could get.

Will clients pay to get their projects delivered earlier? Some will and some won't. Interestingly, we have worked with several major computer suppliers — IBM, DEC, companies like that — who were selling computers, and using computers to design their products, but they weren't interested in the use of their own computer technology to get their plants built faster. This was because their people who were in charge of building the plants didn't have any motivation to use advanced technology; they were only interested in getting the lowest price bids.

We did not get any help from these computer vendors in advancing the technology because of the total separation between the product development and the facility procurement sides of these companies. I personally believe that some engineer-construction company could gain a significant competitive advantage by delivering projects faster. But this will happen only if clients will share the economic benefits of innovative technology with them.

1.14 Group Discussion: Day 1

Eric Lundberg, SPSI, Inc.: I would like to follow up on what Ken Reinschmidt said: I kind of see that NIST has really established themselves in the manufacturing industry. Industry is a credible source for high technology and improved methods and I think by what I see around all the walls in this room is a tribute to that, and the recognition that industry is able to provide solutions.

I don't think that construction industry has the equivalent of that — there is no leader in the industry that can provide the funding and the organizational expertise to get the people together to attack problems that we see in construction. And I think that one of the overall goals of NIST may be to try to establish themselves as that leader in the construction industry.

To do that, I just put a couple of things together. I think a number of people mentioned the fact that in the ATP funding that comes out, there is not really anything focused towards construction and maybe one way to establish that is to actually grant money specifically towards construction for groups in construction to compete against one another instead of against other manufacturing technologies that might be more attractive because of their higher tech appeal. Maybe my second point would be to also look a little bit closer to implementation as opposed to some of the far off technologies — getting to the point made by Clay Claassen of Bechtel —and looking at how you actually implement technology and actually promoting high technology in the construction industry and high tech construction techniques.

I think another issue with construction is that there is really nowhere to turn when somebody in construction has a problem and needs a solution, and one way NIST could establish themselves as a leader for construction is to become basically a database of solutions for the construction industry; recognizing and investigating technologies that could be applied to construction and certainly their vast knowledge of manufacturing and the techniques available in manufacturing could be a large part of that database and be recognized as a source that people can come to and ask questions when they have problems. I think one of the questions was: "would you be interested in participating in a CRDA?," and of course we would. I think that it is certain that a small company like us has to be very cost sensitive and time sensitive, but we're fully in support of participating in a cooperative research arrangement as we have with CERF — they established a very successful arrangement in which we were fortunate enough to participate.

Carl Magnel (CERF): I am only going to make one recommendation and make one point. I would think it would be advantageous to link construction automation as effectively as possible with construction goals. I think that that initiative is gaining momentum — in fact Dick and I will be together tomorrow morning to push this along. And of course Kent mentioned construction goals as well. But you have got to think of something different. It's a difficult industry benchmark and a difficult industry to note progress in and you have to take and leverage everything that you can to get construction automation out there in the forefront and make it.

I would also mention that one thing that we are a somewhat invisible sector — we don't get noted up on the Hill. It is only in the last couple of years that this administration, for example, has made the construction sector more visible by making it visible in the Department of Commerce and elsewhere, and certainly in OSTP. But what we forget sometimes is how important we are to the nation as a whole. We are about 13% of GDP and the only other sector that surpasses that is health care. So we're a big component and the impact we have, or don't have, is enormous.

We are in a situation now where infrastructure renewal is really critical. How are we going to do it? We're not going to do it unless we're able to put the picture in place that the construction sector has some significant roles that they need to achieve and that there are vehicles for doing that, including construction automation, so I would really recommend that.

From CERF's perspective, Eric mentioned consortia effort that we had with SPSI. And I would tell you that we are very much interested in doing that —leveraging industry, the federal sector, to do things that no one could do by themselves.

Mike Sims, NASA : I just want to briefly describe the channel that we have in NASA for taking robotics technology and transferring it into the world. And I want to do that for two reasons. One of which is to invite you to consider proposing or looking at it as a way to get involved, and secondly as a way to bring it up as a possibility for a relationship with NIST because we've been exploring one with NSF.

We have a robotics engineering consortium that is located at Carnegie Mellon University and it is really our way of trying to get all government robotics work to funnel into the private sector. There are three projects we have that are currently on going. One is with Ford-New Holland, where (in 1996) we are aiming for a demonstration of autonomously harvesting 100 acres of corn, beginning in an arbitrary spot and not having particular information about the terrain in the field. You will know it's corn but you will not know the structure of the rows, for example. That is to be determined by the vehicle, before it commences the harvesting. That is a joint program between Ford-New Holland and this consortium. The second project that is going on right now is a project with Boeing to look at automating tracking of their fuselages through their assembly plant. The intention is to track and to control the moving of these vehicles through the plant.

The third project is one with Armstrong Floor and this has to do with the laying of tiles. The first milestone, the first objective of that plan, is to lay the tiles in the middle of the floor. It turns out that in certain applications the automatic laying of tiles looks like economically a very good thing to do. And in a later stage we're going look at laying of corner tiles. The program is set up so that any project that comes in is a 2-3 years program. Its set up as a joint program — in general the contract can be negotiated — but it is typically in terms of 50-50 funding between the private sector and the government.

An in-kind demonstration of that contribution is fine. These projects are in the realm of 1-3 million total project costs. We started last year with several million dollars. From that million we have had corporate contributions into the consortium of $8.5 million so far. That includes sizable contributions for example, from SGI and Deneb. We are interested in relationships with NSF and NIST.

We put in one million and our plan is to fund 2-3 projects at roughly a million dollars each, projects being 2-3 years. So our plan from NASA is on the order 2-3 million dollars per year. Dave Lavery at NASA HQ is probably the best contact if you would like further information on this program.

I should point out that these cooperative research agreements are between NASA and the Robotics Engineering Consortium (REC) and then REC establishes an agreement between REC and the commercial vendor — so in fact there is not going to be an issue of going out to the competition.

NSF involvement to date has been under discussion. Some of these technologies they are interested in. Some are ones that they have been funding for along time. They are interested in seeing those get incorporated into the real world and into industry. It has become so that one of the browny points you get in the national government is from actually taking your technology and getting it out for use in the world.

Milt Gore, DuPont: I would like to build on the suggestion that Eric had concerning a consortium, a technology exchange mechanism, or clearing house. Well I guess my vision is that you have owners, firms, academia, suppliers — suppliers could provide steel pipe or software, whatever — and these folks bring to the table the latest, greatest technology and maybe NIST is the clearing house. And NIST makes sure it is the latest greatest technology, and they keep the database on the solutions of every implentation. I think one of the things that we don't do a very good job of in construction is documenting our successes around implementation. We do a fair job on a lot of things we do and a real good job on a few things, but we really don't toot our own horn, if you will. We don't keep score and I think that is something NIST could help us do. The more you do that, the more you are going to drive the use of the technology.

I think the national construction goals initiative will fulfill some of that by adding benchmarks to make things visible, plus set things off in the right direction. If you got the right mix of funds. Its real difficult from my perspective for an owner to be totally credible and the NC firm to be totally credible — not if they stand alone. But if you can document a success, all of a sudden you get some credibility.

Carl Magnel (CERF): One of the challenges is to put together exactly what you are talking about. One of the things that National Construction Goals says is that in trying to implement that it is quite clear that it is probably going to have to be sector oriented. You are going to have to have residential, industrial, commercial, public works sectors because they are not the same.

Clay Claassen, Bechtel: I'd like to add a comment to the goals approach and the issue of the clearinghouse for technology and making it available to industry. One of the key elements if these concepts are going work is, number one, to actually do some benchmarking and that means in dollars And also set up methods to identify savings that have been achieved with various new technologies, so that you can get some actual cost-to-benefit analysis and ratios. That's the kind of thing that gets some attention in the construction industry, both with the engineering/construct companies and the owners. What can I save?

2.0 Day 2: Round Robin Discussion

Chuck Schaidle, Caterpillar: I'd like to comment on the questions that were raised yesterday afternoon. Did we want to recommend papers or did we want hardware or software? Caterpiller is interested clearly not in papers ... lately we haven't been documenting our own work well enough. Regarding hardware and software developments, let me say a couple of keys things. We need to address major things. There are a whole lot of little fringe items that have to be solved. Hit the major ones. We are interested in major items. This equates to commercializing. Our interest is in earth moving but we recognize there are other peoples' interests in building construction. I say this for CAT machines but its really earth moving machines I'm talking about. We recognize ourselves that the systems we're developing will need to be used on everyone's machine. We can't isolate our machine. A system that will succeed in being a system will have to involve everyone else.

I put these as priorities, but they are more a sequence as I see going through this. If you think about a multi-year NIST program or anyone's program, and our own multi-year program walks in this sequence. Operator information is critical to any form of automation. In this, you can include position metrology technologies, because that is the basis upon which all these others are going to be built. The first step, therefore, is to provide that information to the machine operator, to the foreman, to the manager etc., and then use that information to start helping the operator to control the machine. We call those "skill-enhanced" controls. These may be doing things that the operator is unaware of, or things which take away some of the more tedious functions from the operator, such as raising and lowering the blade constantly. An operator on a bulldozer, by the way, raises and lowers a blade on the average of once a second. So that is the kind of thing I am referring to as tedious work.

The next step beyond that is semi-autonomous, and in that category I would put robotics, and then, as you move on, there are autonomous machines and systems. It has always seemed to us that we build in that sequence, and that there are clearly commercial applications all along this.

When we look at the kind of projects we would like to get involved in, we want those to be very well defined and we want them fast moving. It turns out that if it is not fast moving the benefit we get from participation and any funds that others bring to the party simply get washed out in the time. Time is money and if we're spending more time at something, we would rather spend more money and go faster. And then I say with leaders, and I don't mean that to be exclusive of anyone, but what I really think that it is challenge to all of us to pick out what we are really good at, and focus on what you and your companies are really good at, and bring that to the party. Because that is a real big job and you're not going to have time to play in several fields and play catch up with the leaders. So pick what you're really good at, and bring that to the party.

Some of the specifics, as I see it , are GPS technology improvement. We would be interested in RISC chips in the receivers. These would certainly speed the GPS calculations up and it will bring the cost down. The market for GPS is going to be high and there is going to be enough demand out there to be able to afford RISC chips. What we need are affordable, high accuracy, multi-channel real-time chips. New algorithms need to be developed. If there is an algorithm in the commercial domain and it competes well with the ones that are in private domain then people will use those. Some potential partners in this field include Motorola — where they are doing some research in RISC chips. I know several of the GPS people who are developing their own RISC chips as well.

GPS augmentation: by itself GPS is not going to work everywhere. It will not work in the urban canyons, nor in the western canyons, and sometimes it won't work where you have a high multi-path environment. So anything we can do to augment that — maybe lasers, accelerometers, or gyros — needs to be explored. Some non-GPS location techniques: from our interest we have to get large — a thousand meters. Sure, there are some 100 m sites that our machines work on and I think the SPSI technology is one of the ones that will work there. But really, unless we can interchange between systems our machines move too fast and generally work larger areas. So I think a 1000 meter range — covering a one by one kilometer service area — is really what is needed. Some of the ways for doing that include pseudolites, lasers, and RF. We are very interested in a project in which we take an XYZ that is coming out of a system like that and plug it into the information system that I showed you the other day.

Bill Stone, NIST: *If you were working on a kilometer grid, what would be your required accuracy?*

For most of what we do you are going to need plus or minus six inches (152 mm) of X,Y, and Z to plus or minus a few centimeters. Ideally, you would like to have plus or minus 2 centimeters. Particularly in the Z-direction. It is unfortunate that GPS doesn't work well in the Z-direction (vertical). A lot of applications could get by with 6 inches but if you're setting an accuracy target (for new technology systems), set it at 2 centimeters. A large western mine that will go down a thousand feet would see control of evaluation to within 6 inches at every bench that they go down. The whole mine plans are based on 6 inches maximum deviation from the control elevations.

It is typical now to require grade control on a parking lot to one inch drop across the parking lot. If you get any more than that, the water forms puddles, ice builds in the winter up or the water runs off too fast and washes ditches. If you start getting into paving you're going to have to get down into the centimeter range.

Bill Stone, NIST: *There was a letter that was passed out yesterday which was sent by Gary Sippel of Allegheny Excavating in Pittsburgh. This is around a 50 person construction company which mostly does excavation work, although they also develop office complexes. They use all CAT equipment. His big concern is "how do I get rid of the lasers and inclinometers on the blade and still get that one inch over grade." Even in rough conditions. This seems to be a ubiquitous question in the excavation business.*

Chuck Schaidle, Caterpillar: Onboard display technologies: we need to improve the LCD's in terms of getting cost down, illumination levels up, range of illumination up, cooling requirements down. We'll investigate heads-up displays. I don't know what the acceptance of our operators will be, but many operators have to wear a helmet on those machines anyway. It's an OSHA or MSHAR (Mining Safety Health Administration Regulation). Adding another half pound of weight to those helmets might be acceptable. It needs to be explored from an ergonomics stand point.

Bill Stone, NIST: *When you say operators presently use helmets, are you talking about regular construction hats?*

Chuck Schaidle, Caterpillar: Yes.

Ken Goodwin, NIST: *Those displays are going to just get lighter and lighter. I've seen displays that are just on the back of a computer chip.*

Ron Levandowski, Honeywell: *There's some major re-design in the helmet here. Right now, these helmets are resonably inexpensive. They're not cheap. And they are well balanced. When you add something to it, it puts the user off-balance a bit and it will increase the cost. It may be silly to just say well, let's just add this display to our existing helmets. Rather, let's look at a design that incorporates this display in a new type of helmet. With the state-of-the-art in surface mount technology that is coming out now you can almost inlay that equipment right on the inside of the shell.*

Chuck Schaidle, Caterpillar: I'm not convinced, from CAT's point of view, that the operator will prefer to have it up there on his helmet, as opposed to an easy to see location somewhwere in the cab.

Any applicable software for managing the data onboard, off board, single machine or multiple machines, or whether it's the management software, the monitoring diagnostics software, the plans, any of that, and the software that drives the information displays. Those are projects that we would be interested in participating in.

Another area that is in need of research involves pushing the capabilities of wireless data networks in a multi-machine environment. Often times, this will involve large obstructions in between and with some very high data rates, and with high demand that the data be accurate.

Bob King, CSM: *I think that there is a link here in terms of looking at architectures for large volumes of data and very high rates.*

They all sort of tie together in looking at a software operating system that maybe you can use to support parallel processors, rather than just a single RISC chip. I think there is a whole system that is necessary to handle these extremely large volumes of data and extremely high data rates. Especially when we get to the time of video data rates.

Chuck Schaidle, Caterpillar: Along those lines, two of the systems like the one I showed you yesterday was running with a separate computer doing the GPS calculations and another computer doing the information system. We have multi-tasked those two computers and we've also had all that done on one. At any given time, there is no preference but our preference over the long term tends to be to keep these things separate so that the individual technologies and individual component suppliers can move at their own pace.

So what in fact we have been encouraging GPS suppliers to do is to put their computer back in their signal conditioning box — give us an XYZ and time and we'll take care of it from there. Sure you could do it with one chip but then every time the GPS supplier changes its chip you have to change your system. The same thing applies to the software. Yes you can tie your display software to your data management software but I think somewhere down the road you're going to want to do that. At this point all these things are moving too fast developing too fast. Our approach is to keep it simple.

Bob King, CSM: *My point was not to tie them all together into one machine but rather that it would be a good thing for NIST to do in support of this activity is to become that information center on the lowest cost parallel multi-processor machines and information on how operatoring systems can effectively utilize those multi-processor machines dealing with this data. One multi-processor machine might be a GPS technology; another multi-processor machine might be for management of data for the whole site. I wasn't inferring that everything go to one central computer.*

Chuck Schaidle, Caterpillar: I think what your saying is for NIST to look at what is out there in the computational and storage areas and to say, "how could we adapt that to construction." The NIST group that is involved with construction automation should not try to drive processor technology. We're kidding ourselves — we are not that big — to drive processor technology.

Bob King, CSM: *We're talking about having an information database here at NIST or NIST being the source of information for improved construction techniques. This is one part of that piece of information that NIST could be gathering that would serve this activity.*

Chuck Schaidle, Caterpillar: One thought that we have been wrestling with is when you do work down here in this software and database, you need to think about that being compatible with whatever processor and whatever operating system environment you're going to be working in. You can't afford to be rewriting and setting new standards every time Motorola or Intel comes out with a new chip. We see RISC (Reduced Instruction Set Chip) as being key to all this. RISC is a chip that is cut to run spe cific calculations. It is not very flexible, but very fast.

Jim Albus, NIST: *One of the things we've been looking at in the manufacturing area for is what is the information that is needed to move from one module to another? What you are saying here is that you'd like to have a GPS module that just gives you XYZ and my guess is that there are a bunch of other kinds of modules like that that you would like to just have the data that that thing is supposed to produce and what you'd like to be able to say is, "I need that data to a certain accuracy. Now you tell me how accurate you are giving it to me. You give me some parameters that characterize the data, including undertainties, and somebody decides on how fast you'd like that data. Either you tell them how fast you want it or they tell you how fast they can give it to you. So you want the data, you want to have some way of specifying how fast its going to come, how precise it is, something that characterizes the data. That's the kind of information you want to into that box or get out of that box. You don't care what's in that box. That's the GPS guys' business what he puts in there. You don't care as long as it works.*

We're interested in thinking about that data exchange. That has been our thrust for a number of years. We try to figure out what the functional modules are and then worry about the exchange ,that's the way IGES works — we don't care what's in the CAD system as long as your data is in standard format. When the data moves from one place to another it has to be in a standard format. I think we would be very interested in working with you and listening to your ideas , and maybe you could organize with some standard committee to look at the issue of what are the interfaces, the message protocols , the formats, what is the information content. It's sort of like the application layer of the ISO standard. That then gives you the plug-and-play system capability. Okay well say that I got 35 companies that make GPS systems. If somebody else comes up with a better one I would like to be able to pull the one out that I got out, put their in, and expect it to run.

Chuck Schaidle, Caterpillar: It goes way beyond GPS. I would like to take the survey data that comes off of anyone's survey system, whether it's GPS-based, total-station based, or a fly-over digitized map. It gets complicated pretty fast. I think what Ernie was showing yesterday is a start. It is a layered environment. Another question we are often asked is how accurate does this have to be, what is the minimum cell size. The minimum cell size depends on what the application is. It wouldn't be too bad if you say for mining it's one thing and for parking lot construction it's another. But then it gets down to what machine you're using, because some of these machines are working to much less exacting standards and are getting data every meter. Then it get down to how fast the machine is running; that's when you start getting into information display. If you only have data every 10 meters, the question is, "what do you display to the operator when he's between those data points."

It is not acceptable for him to be shown one piece of data and then immediately jump up to something else. So either you have to interpolate between those — and you hate to do that if you have good data. If for some reason now you come along and you take that dozer that went over there and its got survey data all the way along there, you do not want to throw out 9 points and save 1. So it gets into the problem of making a gross-accuracy database compatible with a very detailed base. And you can exchange data between a gross database and a detailed database.

Jim Albus, NIST: *You know we run into that at a completely different scale in the inspection of machined parts. Now were talking about a thousandth of an inch resolution or 1/10,000th of an inch resolution. When you machine it, you've got to size it. Often, when you inspected it you just touch it in a few spots and make inferences as to what is between those spots. In fact, one of the projects that we are working on right now involves collecting data using optical sensors and stylus probes, and passive probes that fly over the surface. All that technology is being developed for things like turbine blades, but you could quickly apply it to things like improving the accuracy of a grading maneuver. It's just three orders of magnitude difference in scale.*

Chuck Schaidle, Caterpillar: Another analogy is finite element analysis for structures — you can have a gross grid until you come to a weld joint (where you have high stresses) and you want a detailed analysis of that area. Then you go out and test it, and it breaks somewhere else. Now you have to go in and do a detailed analysis of that new area. Our machine, the dozer, when it leaves the office it drives to the site where it's going to work, with the same database that it uses to do the work, but with a totally different data intensity. You have to do that. The highway map — the road out to that site may be ten years old, but you've got a digital map, you can't afford to go back and redo that.

Jim Albus, NIST: *There are also some interesting applications now with military unmanned ground vehicles where you in fact want to drive without an operator, and be able to give the vehicle a command and have it come back by itself — using inertial or GPS data that you recorded on the way out. You don't want any radio transmission after a certain time. Lots of potential leveraging of this technology.*

Chuck Schaidle, Caterpillar: I am not sure that any of us in this room are good data managers. You need to be looking at the AutoCADs etc.

Kent Reed, NIST: *We're better than you think we are (laughter).*

Bob King, CSM: Chuck, I think this concept applies — we've been using positioning data as an example and of course at a construction site we would be earth moving, building, whatever. There are a lot of other kinds of data, and they all have the same need. For example, when we do the system help assessment with multiple sensors on a machine ... you mentioned 65 or a hundred, however many sensors we have on the machine, we don't save every data point. We collect data at a very high rate, but we are continuously testing these data points and if we see a linear situation - a straight line — developing, then we just have a equation with that line. Only when it doesn't fit the straight line, we run a good test, do we save a point. And so what you are saying is that there are some instances were you just need gross data. And other instances where you need higher frequency data. That applies not only to positioning, but also applies

to ten different types of data on the compression cycle. It just not just positioning data that you should be considering.
Bill Stone, NIST: *You gave us some number there: plus or minus 6 inches in one case, plus or minus 2 centimeters in another. Perhaps this is something that Milt (Gore) can answer better. When you are talking about putting up buildings and other types of major projects, what is the accuracy that is really needed if you wanted to know that something was put in place properly?*

Milt Gore, DuPont: I haven't been involved in too many building projects other than blast resistant control houses on federal government projects but generally we're looking for single story buildings we need to be better than quarter inch.

John Schlecht, Ironworking Institute: *Structural steels fabricate plus or minus an eighth.*

Jim Albus, NIST: What is the limiting factor or tolerance there? How good could you do it?

John Schlecht, Ironworking Institute: *The limiting factor is the bow and the sweep in the hot rolled shapes. Every thing really is fudging back from the mill tolerance.*

Bill Stone,NIST: We have talked about a good many things here in the last two days. Earth moving seems to be one of the obvious candidates for automation — one that people always tend to think about. But there is another facet to this that relates to what Milt Gore at DuPont was saying yesterday, where they are looking at on-the-ground prefab segments and lifting these "value-added" units up and assembling fewer, more complex macro components. That concept applies to a lot of things, not just in the petrochemical industry. The idea would be that if you prefabricate something it would be nice to do automated "docking," as the guys at NASA would say, and have it automatically assembled. You can connect that prefabricated component to a crane and bring it in and have it automatically recognize where it has to go. The reason that I say this brings me back to the question: "if we are autonomously contolling a crane to bring in a wide flange steel section that is going to be bolted in place, what kind of accuracy would have to be maintained such that a guy could go up and slap the bolts in and then go ahead and take over?"

Clay Claassen, Bechtel: *We are talking about two different things. One is fabrication tolerance and the other is erection tolerance. And the answer on erection tolerances is, "what is the demand of the envelope you are working in." For example, any elevator building has exactly what you are talking about. That is, a module inside the structure that has to operate within a certain tolerance. But I think normally, and I'm not positive on this, but I think then you're talking about halving that tolerance down to about a sixteenth of an inch. But of course that is over a distance. You keep coming back to the plus or minus sixteenth as you go in vertical envelope — which is called plumbing, or a plumbing-up operation.*

I think it's hard to come with a standard for structures. It depends on what the structure's requirements are. I think back on a project we had few years ago down at the Kennedy Space Center. We were building a large *launch complex structure where it was a moveable launch complex structure about 30 stories high and it was on huge railcar wheels. And on the front of it was a door that would swing open. The door is a 150 feet tall and about 75 wide and weighed about 125 tons and we had as far as positioning for installing door, we had to check the steel at different parts at different times during the day. Depending on the thermal effect of the sun on that structure, even cloudy days versus sunny days, we had to perform those measurements to see how the structure reacted to thermal expansion/contraction before we determined how that door will fit. It all depends the kind of application you're talking about.*

Milt Gore, DuPont: Those requirements — that building envelope requirement — is a standard architectural consideration in your specifications for the curtain wall, the elevators, and that is one of things that you do in the plumbing. You have to allow for the time of day and the temperature.

Bob King, CSM: *To add to that, in the high wall mining application that I mentioned yesterday — of course we don't have GPS underground and we commonly use a sensor called a ring-laser gyro ,and in that application we been able to achieve about 1 inch over 2000 feet. And that is necessary to keep the pillars of rock between those two high wall entries straight so that you don't leave too much material in one and cut out the material in the other and end up with a collapse. DuPont has an underground coal mining subsidiary called Consolidation Coal Company that uses a mining method called Long Wall mining, where they start at one end of a long block of coal and just take a slice all the way along that block of coal, and it might be a 1000 feet long. So that they obtain an even slice every time, usually each slice is about 42 inches thick, they have a laser alignment system that keeps them over that 1000 feet within an inch of precision.*

Clay Claassen, Bechtel: The important thing as far as positioning is having the capability of collecting positioning data from a variety of sources and, depending on the information you are trying to collect, making that available at the construction site in a common format. That positioning data has to be able to be collected and recognized on a real-time basis. You have to be able to integrate positioning data from whatever source it's coming from into a common program so that you can represent what you are trying to describe. It has to be translated in a manner where it becomes visual to the people that are going to be using the data. It can't be in abstract form, it has to be displayed in a manner that is understandable and can be related to what an individual is trying to accomplish. So, you have to have a lot of flexibility in a system that is going to either satisfy earth moving operations, steel erection operations, equipment installation operations etc.

***Bill Stone, NIST:** If I read you correctly, you are suggesting that there ought to be a standard digital format for metrology sensor output, such that it can be recognized by any standard package as to the rate, the accuracy, the repeatibility and things like that for that type of sensor, so that any program then could get data and say, "Oh this is a low grade sensor, it is going to update every second." Then maybe whoever is using that can set a flag which says that you can't do that for this application, it's not accurate enough.*

Then you have a suite of technologies. Then, if you had a job where you said you have to control to 1/16 of an inch over a 20 story building *and click on GPS, the system is going to say, "sorry, not accurate enough to achieve that tolerance." You have go down and figure out what other technologies you have available to you.*

Clay Claassen, Bechtel: I want to clear up one thing. We may be skating off on very thin ice here. These tolerances you are talking about, in steel construction, at some point along a beam or a girder or something like that your tolerance may be, because of bow and sweep and shape, you may be off by half to three quarters of an inch. You come back to your tolerance at the connection in the plumbing operation. In other words, you are never going to have a grid along a member where you are always within that 1/16 limitation. I think maybe there was a little misinterpretation there. The thing that controls the tolerance is the actual rolled shape, which is to a fairly big tolerance.

Bill Stone, NIST: I guess there are two things. In my mind I don't think steel erection is going to get the stage in the near future where it is done automatically. There are going to be people up there who are going to be making the connections and the placement as the components are brought in.

Ken Goodwin, NIST: *Not necessarily. That's exactly what Lehigh has been working on at ATLSS. You need +/- 1/4 inch to place those. Its a wedge shaped connection which gives you larger tolerences for the initial mating maneuver. If you go to different type of construction like that, when you go to an assembly now you are doing this plumbing and you are doing a lot of adjusting. If you could go to a self-aligning and self-plumbing system — something like the Lehigh connectors — it would pull things into compliance.*

Clay Claassen, Bechtel: As far as commercial building construction, you are working to a larger tolerance with concrete than you are in steel. So you are always going to be controlled by a broader tolerance, where your footings, walls, and all that other stuff goes, and interface -- where one material frames to another. So it is always a process, in laymen's terms, you are always getting out to a point and pulling back to what your tolerance might be and then that's what they call in steel "plumbing it up." When you have a bay in place then you pull it back to within your required tolerance.

Ed Pendelton, SPSI: *I would like to summarize some of the things that I've heard here. As far as what NIST can do, I think you should think about what you do best. And what of those things I would say is setting standards. I picked off a few of the areas mentioned on the information sheet we got before we came here, including virtual site simulation and object representation. We talked a lot about positioning information which is certainly an interest of mine, and of SPSI, but there are a lot of other elements out there to keep track of. We know this will be critical for a fragmented industry where you have a lots of different kinds of folks trying to talk to each other. You need to have those standards so that we all can speak a common language.*

A second area I see is lessons from manufacturing automation,because I think there is a *lot to be learned from this that is applicable to the construction industry. And I'll give you some counter examples with our technology (SPSI) we're not just looking at construction, but going into manufacturing. We are finding a lot of interest in manufacturing for our technology. So maybe here is a case where construction can teach manufacturing something — we'd certainly like to think so.*

I think there is a lot we can learn from NIST with regards to their experience with manufacturing automation. In terms of data communication, this is another area mentioned ... wide band telemetry and data acquisition. If you look at all the presentations we saw yesterday and the job sites of the future, if you could visualize what the EMF signal would look like it would look like a ball of fire with things going everywhere. So I think that is going to be a real key problem and I know that is one of the problems we are always constantly working with. With our system ,we don't have any problem getting information at the user site, wherever he has that instrument. But getting it relayed back to a station on site to be used at a CAD station is a problem.

With regards to question #2, whether we would be interested in CRDAs, I have to take Eric, who is the technology guy for SPSI and I am the marketing guy so I come down a half of notch, I say CRDA maybe, but it depends on the application for us and then I sort of slipped this in this morning after Bill said "grants," and I say probably. So being a small company ,we're always interested in what we might be able to do to partner up with folks and to further develop not only our technology but others as well where we can help.

Jim Albus, NIST: You should be aware that under a CRDA, the companies that we deal under CRDA can own the patents that come out of the research. If we give you a grant, we own the patents.

Ed Pendelton, SPSI: *We have come up with a very innovative technology, but we're faced with coming up with an equally innovative means of marketing the technology to the construction industry. So I think that its key that whatever NIST does here in terms of furthering certain technologies, to really keep in touch with the customers here. Sometimes that is a very difficult thing to determine in construction. There are a number of customers. It could be owners, architects, engineers, and designers, any number of folks. So that's what makes marketing to construction a difficult task. It's not always clear exactly who your customers are going to be. Other than that,I would like to say anything that will promote new and emerging technologies, as Clay mentioned yesterday, of course we are very interested in because we think that we have very exciting technology and will be used quite a bit not only in construction but in other industries,and we are certainly looking forward to working with NIST now that we have an office in Reston.*

Bill Stone, NIST: Do you have any comments, Mike (Sims), about data communications. We talked about this a little bit yesterday but the idea is, if you have hundreds of Dantes (CMU autonomous robot tested in August, 1994 on Mt. Spurr, Alaska) out there, you said 50% of your time on a mission was spent setting up the communications links. What do you foresee as the bedlam (or lack thereof) in trying to implement that on a construction site?

Mike Sims, NASA: *Our systems are not traditional for every site. We are in the realm where we go and perform a week long field test or possibly up to several months, but it's really a different setting each time. My first guess for implementing this technology at construction sites would be to go out and try standard commercial packages, such as radio ethernet — set yourself up in an environment that has a protocol for communication and see if that meets your needs. If it does, great. You can then easily get multiple machines communicating with each other locally via radio ethernet.*

I don't have any direct answers to how you would deal with the problem of having a hundred Dantes out there, trying to get images back. The first thing I would do is I would say, I would be real careful of taking something like that to be a requirement, because it's sort of looking and projecting what might occur. I would rather try to take actual situation paths and see what the requirements are on those and see what that volume of data coming back really looks like.

Chuck Schaidle, Caterpillar: I'd make a comment on that. The need is more immediate than that. We have more than one customer that's operating in excess of 50 machines that wants to equip those systems that I showed you yesterday on each of one those machines. That customer wants each of those machines inputing and extracting data from a common database that is also tied to their engineering planning system and is also tied to their management system to calculate things as fundamental as productivity on a daily basis.

Mike Sims, NASA: *Those bandwidths could be very small. If you give the machines at some point initially their own databases and they only communicate back and forth critical pieces of that data. The required bandwidths can be dramatically reduced. It may not yet be an issue. If you were telling me that you had to get real-time video back on all 50 of those machines I would start to worry about how we were going to do that.*

Let me follow up on a comment — if go to the point of defining standards or protocols of communications among various data sets we have in construction, I think it's useful to be careful about what kind of data that is and where standards may or may not be useful, and what those standards might be. What I mean by that is, take an example of the image data, two dimensional image data. There are dozens of formats that image data is written in. In fact those dozens of formats are fairly well known, and if you go to a reasonable environment you could take any of those dozen formats and put them into your system. So from the point of view of most of most of those, it doesn't matter, usually. So in terms of the data that I am getting back, which looks like an image, for which the format is not terribly important, but what I don't know about is that there is not an agreement. There is an agreement on how to communicate a certain type of data — it's this XY data form. But there's not an agreement on what that data means.

So there's not an agreement on, for example, protocols as to whether this image represents a square centimeter or a square kilometer ... you just don't know that. Sometimes it is embedded in the headers, sometimes its not, but there is no protocol about it, there is no standard. In fact there are no standards about what that image data is. You can embed all kinds of data inside that particular image format and we do it on a regular basis, *and really then it's not an image at all. So when you gather up this piece of data you don't know what language it's speaking in. So, that is an issue about who actually knows the content of the data.*

Traditionally in programming, we do that by making notes in the source code. So the programmer has it in his head and then they embed the content information in this coded form and the code passes back and forth this string of very compacted data. But it has no information about what's in it.

As you get closer to object-oriented ways of dealing with information you tend to try to start putting some of that information into the data itself. My point is that there is a distinction between the actual format in which you are transmitting data — which allows you to communicate among various elements. In fact I would suggest that the way image data does it is very different, in that very powerful compression processing is involved to effectively transmit that kind of data. There is a whole other suite of image data that is useless to do. You don't know enough about it to use that data.

On the other side, what is the language of communications? If you want take a data set at XYZ location you can do that. What is the systems of units you are talking about? Is there a common language we can agree upon enough to say that this piece of data is, for example, topography. Or this piece of data represents coloration. I don't know what the right parameters are. Is there enough commonality that you you know where to go to find more vocabulary then say, "this is what that data is." There is this fundamental issue of whether to embed that information in the data or not to embed it.

In recent information work, it is not embedded in data for several reasons. One is because it is less efficient to transmit the code than the data. If you put more information in it it becomes less efficient to transmit. Sometimes that is significant and sometimes it's not. Another reason it's not often done is that it's hard to do. It takes more work to create data sets which have information in them than it does to create data sets that don't.

So ,image data we use all the time contains virtually no information even though we could put a header into it in various formats. But typically there is none there simply because it is to much trouble to bother with and there is also the problem that once you've decided what this is, is it really more work or less work if somebody else could use that?

The idea of transmitting data from, in the sense of that the data in and of itself knows enough about what it's doing that the data in a sense becomes self-readable. The data can be transmitted in a format that's useful. It is an extremely powerful idea at certain levels of abstraction, but as the world is right now I don't know about the future. As the world is right now there are certain levels of abstraction in which I am specific enough that putting more information in actually slows down post-processing.

Bill Stone, NIST: That would be in something like updating a full screen video frame whereby the header would take up refresh time?

Mike Sims, NASA: *I am not worried about that per se.. For example, when we go on a mission and we come back with thousands of images — lots of data space. We also take those images and process those images in lots of ways. As it is right now, we don't keep* *track of the history of those process changes. We always keep a raw set, but we don't keep careful track of the history of those process changes to that data, except in our heads. That might be extremely useful. But the overhead to getting it done right now doesn't justify our time. People are, in fact, very good at keeping track of such changes. So as of right now that additional piece of information — "this is place XYZ " — with lots of header stuff would be useful, but we cannot include the entire history of how that data has been processed.*

Bob King, CSM: I'd like to get back to what was said yesterday about automatically creating the as-built drawings for a site. This is very closely tied to that activity, and I think a lot of the ways we can reduce the data volume, like you said "not send stereo images with all the information in them everywhere,", is simply to have models and a sort of a pose of each model, a position and orientation of each model. And as that pose changes, that's what we transmit: the item which identifies each object and its new pose, rather than trying to transmit complete video images.

Bill Stone, NIST: *I think in the case of when you're talking about position or orientation, particularly in terms of a vehicle, I think you're right — you can have packetized information that has a binary byte that identifies the type of machine and then it might be two bytes if you want to cover all types of known construction machinery, but probably not more than that. So you would have an encoded packet. And there would be another packet for XYZ and yet another for theta-x, theta-y, and theta-z. And there might be a few others to cover other general articulations. I don't know how much that would end up being, but it would certainly be more on the order of several tens of bytes at most, as opposed to a megabyte per frame at 30 hertz for video. It would be for these smaller packets that data exchange standards might prove useful.*

Bob King, CSM: Somewhere you have a knowledge base of all these models.

Bill Stone, NIST: *Exactly. So that way somebody like Chuck (Schaidle, CAT) over there — if they have a very complex piece of equipment that has just come out, maybe it has ten degrees of articulation that they want to know about, they have a standard representation format to work with in describing that machine. The standards people on the other hand have to allow up to, say 20 different arculations in their standardized kinematic model. Then it's up to Caterpillar to assign what those mean. When you get down to video, that's a whole different ball game. We have to ask questions like, "where would you need video and what would it be useful for?" I'm not convinced that real-time video is required in most practical situations. It is in the case of teleoperation. For that situation you need it. But not for 99.9% of the average construction sites in the U.S.*

Kent Reed, NIST: Let me remind you of my comments yesterday morning about digital standards. I think you'll find that from now until the end of time you will have a lot of different standards. You certainly need to think about an architecture. It may be the same syntax that we use in every layer of the architecture but the meaning in each case will be quite different, depending on how much information is passed and how fast and who really needs to know about it. I would really be nervous about any standardization effort that starts off saying, "how many bytes do we have to work with?" I think that's the wrong end of the telescope.

Bob King, CSM: *A lot of earth moving operations require this positioning data and other data to go into different types of software packages. You mentioned a couple ones — an engineering issue management system and a planning system, an inventory system and so on. I know that Jim (Albus, NIST) has worked with Ray Harrigan at Sandia where they have or are beginning to build a standard called the GISC (Generic Intelligence System Controller) system. It's really not DOE's pervue, but because such a thing didn't exist where they could merge let's say a kinematics and dynamics modeling package with a robot controller with a real-time expert system with another piece of database software,and so forth and so on. They wanted a standard way of interfacing all these different software packages that you can buy from a large number of vendors, and that certainly is a worth while endeavor which has applications in construction as well as manufacturing.*

John Schlect, Ironworking Institute: I have both a question and a statement along those lines. Does NIST have a role in an effort combining with the American Institute of Architects, the American Society of Civil Engineers, maybe the American Institute of Steel Construction to ... I am looking at this presentation of construction bottlenecks from yesterday afternoon and it asks the same question I was trying to ask yesterday: Can structural drawings be electronically transferred to create and automate reinforcing steel fabrication and placement drawings? And then obviously the next thing would be robotic placement, for example. And then in the structural steel arena, basically the same question: can the task be automated to develop directly from the structural engineer's drawings?

You need to be concerned that downstream interfaces involve big lag times, including getting in a mill order, generating shop drawings etc. Caterpillar says there is an end product, but all those phases leading to the end goal could achieve tremendous improvements in efficiency if we had a standard for data transfer through each of those phases.

Kent Reed, NIST: *That is exactly what we are working on with STEP. We want to maintain histories of manufacturing back to the materials that went into the components. The Europeans are ten years ahead of us. We need to focus on all the pieces, so that the end results come out better. This might suggest another workshop that is a bit more focused than this one.*

John Schlecht, Ironworking Institute: This is the first time I've heard of STEP. But I'm new at this job.

Clay Claassen, Bechtel: *The idea is to permit raw data generated in each phase of the engineering and construction to pass through to the next. STEP is attempting to do that, in order to eliminate some of the reformating of information — essentially the same information — which sees slightly different use depending on the current phase in the process. What we need to do is eliminate the middle men. We are presently reformatting numerous times information that really hasn't changed. We generate different information for the procurement process, the field engineering process, the fabrication process.*

All of these people are just re-interpreting the same information and what we really want in the end is simply to get that information in a useable format into the hands of the people doing the work.

Kent Reed, NIST: All that reformatting is at best value added and, at worst, noise!

Ken Goodwin, NIST: *Does STEP incorporate topographic information? Does it embed information concerning where things are as well as what they are?*

Kent Reed, NIST: The structure of STEP allows for all types of information. But there are not many people working on those aspects. Furthermore, the construction industry has been slow to bring those concepts that it finds of concern to the table. In process plant design, we are able to convey information concerning shape, location, interference geometry and tolerances etc. The real question is, "what topology do you want?" Do you want to capture every phase in the construction process?

Bob McClelland, Fluor Daniel: *What we would like to see is a totally integrated information exchange system involving , by automation, transfer of design data, material/procurement information, progress status, etc. We would like to be able to do that between all disciplines involved in an engineer-construct project. Such a system would involve interfacing design systems, material control systems, project controls systems, and field supervision systems.*

We think that bar-coding and wireless transmission of data to a jobsite server is a good idea. You need to send that information to the people who are in need of receiving that information and screen it from those who don't want or need to see it. The use of penpad computers with radio ties to a jobsite server would eliminate a lot of paper. When you are up 60 feet and the wind is blowing and its hot the penpad is a real advance. We are using it on a project right now for redlining. As built, they come with onboard PCMCIA cards and a 250 megabyte hard disk. They can carry all the drawings they need out to the field.

It is encouraging to hear that most everyone here has the same train of thought. Let me reiterate that an important aspect is to make sure any personal digital assistant (PDA) speaks the same language (data) between different systems — whether its designed on AutoCAD, PDES, ProEngineer etc. They must be able to talk to each other.

Let me finish with just a few words about Fluor Daniel. We may be interested in a CRDA partnership, but this requires VP approval. I, as an individual engineer, would be interested. Fluor Daniel Technology (California) would likely be the tie-in point since their interest is blue sky technology. What I've seen talked about here during the last two days is of interest to the construction division.

Early in the day, someone made the statement that maybe NIST was not such a good platform to encourage the implementation of new technology in certain government contracts. Keep in mind that NIST is involved with standards and technology. I think, contrarily, that it might be possible, and useful, to write into the standards and specifications on certain government contracts the provision for the inclusion of new technologies.

Kent Reed, NIST: We have helped the Navy write specifications and have helped our own procurement division write specifications. Where we see problems is in defining what constitutes a working database; what constitutes a release database; how do you embed license stamps and seals — as in who authorized this drawing or who stamped it. The technology exists, but establishing the business authorization is hard.

Mike Sims, NASA: *There are widely used commercial software version control codes out there.*

Bob McClelland, Fluor Daniel: Here is our bottleneck: we have invested a large amount of effort designing our plants in Intergraph format. We would like to issue that model direct to the field, but the drawings have to be stamped. So we are stuck — we presently have to print out a hardcopy, stamp them, scan them back in, and then we can issue them.

Kent Reed, NIST: *The real issue is how to achieve this integration. It's useless to talk about technology when business practice is the block. Bob (McClelland) talks about the potential for a digital P.E. stamp. So, how is tort law going to handle such things as digital notebooks, stamps, signoffs. There are no established mechanisms for dealing with this right now. What this creates is new exposure to risk. You can just imagine going out and getting a lawyer to convince a judge that you didn't assume responsibility for some job. What is the verification mechanism for this digital P.E. stamp?*

Another point that was brought up is that knowing your customer is hard in the construction industry. Plant STEP is such a consortium. And yet various parts of Fluor, for example, have been approached and don't seem to be interested.

Bob McClelland, Fluor Daniel: one part might be interested; one not. I'd suggest you contact the Technology Center, whose mission is to identify new technology and partnerships that Fluor could benefit from. Another likely group is Ken Reinschimidt's part of Stone & Webster.

Kent Reed, NIST: *a consortium works for some and not for others.*

Bob King, CSM: Do you have a phased approach toward getting to automated information exchange?

Kent Reed, NIST: *Yes, it's going to take several years to implementation. This was described yesterday by Dick Wright and is detailed in the BFRL report to the National Science and Technology Council. There are several initiatives that have been proposed to halve the cost or manhours of doing a particular activity. The initiative has seen different names, but overall, the idea is to integrate the various tasks so that all participants can communicate together.*

Ken Goodwin, NIST: The ATP program experience with the medical industry showed that what they really wanted was an integrated information system, not new technology. The next step is to develop new means for the integration of information. ATP grants are now being made for developing the missing technology in that area. So, in the construction analog, what are the missing technologies? I think we need to enhance communications between various systems.

This could be a step in the right direction for NIST. We need, for example, a generic means for STAAD 3D to talk to PDES. For PDES to talk to Prima Vera etc. Right now there is no field superintendent's Planning and Reporting package -- something to help them know what equipment is on site, what's available and to use the PDES model to plan activity. And there is still the issue of tagging information to components.

Bob McClelland, Fluor Daniel: *2D bar coding is a few years away. It may be a good idea to have one standard for everything. 2D coding can contain the equivalent of an 8-1/2 x 11 sheet of paper in information content — but there is no national standard yet. For example, you have a pump out there. The drawings could be contained on the 2D bar code, as well as the build date, the operational data sheets. Furthermore, there are memory buttons out there as well that can hold four megabytes of data (16 pages plus graphics). You can extract information from these, or rewrite to them. They have a ten year lifespan. From our point of view, it would be extremely beneficial to be able to send a PDES drawing to vendor, instead of design drawings (hardcopies), and say, "build this".*

Kent Reed, NIST: I'm always shocked by how little information content is included in the uniform bar code system. If you go to the grocery store and you scan a carton of milk, you can trace back to what vendor it was and what that product cost. But if you scan the carton of milk next to it you have no way from the bar codes of knowing that both are discussing bottles of milk, or even that they are both generically discussing the same kind of grocery product. It is an incredibly backward system; so if there is a need in the construction industry to have better marking of materials, then they need to fix the two dimensional code. Here's the opportunity to try to make it smart.

Bob McClelland, Fluor Daniel: *We're working our vendors to try to come up with a more intelligent one-dimensional bar code that supplies us more information. I am not working on that specifically myself but there is another guy that's sits a couple of offices down that does nothing but work on bar codes.*

Ernie Kent, NIST: I think if we have the right kind of information exchanged between different packages we begin to give that site superintendent the tool that we were talking about yesterday morning, which is the ability to deal with "what ifs". What if it rains tomorrow? So we have some material properties about the soil and we know, "is it OK for this dozer go ahead and work on this particular site tomorrow?". What if this critical piece of equipment is broken down? What else could I do on this particular site.

Bob McClelland, Fluor Daniel: *What if it's going to rain. Do I have the material in the lay down yard to go and work inside tomorrow?*

Ernie Kent, NIST: Right. That's really where you want to get with this. You are not just after information exchange. You might get, in a couple years, to being able to exchange all this information. What's the real value of that? Well, the real value is so that the superintendent doesn't have to spend all his time writing all this information down and filling out reports and so forth. The superintendent can now talk about, "let's do this what if analysis every day and plan what we're going to do the next day.

Bob McClelland, Fluor Daniel: *We are currently using the PDES (Plant Design System) model. We have it implemented on an Intergraph system. It is capable of containing a great amount of data including material delivery, orders, purchase orders, specifics in size and dimensions and weight of certain things. So, it's got the space in its tables to give any object on a screen-specific entity and that's what we'd like to do is give those items specific entity information so that the superintendent down in the field can click on that piece of equipment and pull up reams of data.*

Bill Stone, NIST: At this point, our time is up. I would like to thank each of you, and the organizations you represent, for taking the time to participate in the past two days' discussions. We will look forward to your continued advice as we move towards implementation of our initiative in construction automation here at NIST.

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Appendix B: Letters from Industry

Gary A. Sippel
Allegheny Excavating

I am the president of Allegheny Excavating Inc., a commercial site development contracting company in Pittsburgh, Pennsylvania. Our primary work is site development for shopping centers, retirement villages, and housing plans.

In my 17 years of business, I have seen the industry move from transits and levels to the present use of EDMs and grade lasers. These instruments depend upon a direct line of site which presents a problem at times.

We begin our bidding process by reviewing a blue print drawing of, for example, a 60 acre heavily wooded site. Suppose the drawings show building locations on this site for a shopping center. Under this building is a 45 to 50 foot cut with 600,000 cubic yards of earth and rock to be moved.

In order to accurately determine the amount of rock excavation by core drilling, we would have to locate building corners in the middle of a dense forest. This procedure requires partial clearing and surveying to get an accurate location on the building and surrounding areas to be graded. This process can get very costly.

It is very important that we establish control points for our test boring and locate them on the prints. Then we log these points into our earth works program, so we can determine an accurate quantity of rock strata.

As we start construction, we search for limits of work. We always used an engineer to establish property lines and limits through over-grown areas, peaks, and valleys. Because the site is not table top, this requires major control sets by an engineer, all of which cost money.

Once the site is cleared and we move on to top and bottom of slope, the most critical locations are fill slope (which could be 200 to 300 feet long) or a cut slope (which may be 100 to 150 feet long). Due to these lengths, locations and elevations cannot be off. If they were inaccurate, once you reach the top of a fill and you have a road or building, you cannot go back and add a sliver of fill or cut a sliver on a cut slope.

As earth moving continues on the site, some times we are asked to provide two building pads totally remote from each other, with a major mountain in-between them. Once again we have to have our engineers set up control and shoot each pad separately. This is so that once the first pads are done, the general contractor can begin constructing the first two buildings while we are moving the earth between them.

As the project enters its final stages, we bring the site from a rough woods to within a tenth of grade. We use our grade lasers in combination with blade controlled sensors on our scrapers, dozers, and graders to cut and fill to meet final sub-grade. The need to know elevation, and location is necessary in order to complete this operation.

The laser equipment is good on a 2 or 3 acre building pad or a 10 acre parking lot, provided that the grade does not change. Once there is deviation and grade change, the instrument has to be set up again at a different location and different percent of grade.

In general, the laser equipment is good because it is accurate, cost effective, and efficient. The problem is in order for us to use our laser effectively, we must be provided with location and elevation control from an engineer. This takes a lot of engineering backup and control to establish. I have always thought that there has to be a better way to control elevation with location.

Relating our need with a company in our complex which sells tractor trailer locators. This system uses a satellite to determine where a truck is and if it is in transit. The only problem is that this degree of accuracy is far too wide for construction use.

As a contractor, our needs are by use of an aerial beaming device such as a satellite or sound device. A contractor could use the design engineer's layout on computer and input field reference points, such as property corners, into the computer. This would enable us to take a sensor and or a laptop computer to certain areas of the site to establish the limits of clearing, boring holes, top and bottom of slopes, building corners and pad elevations or certain areas in the parking lot or roadway and define an exact location and elevation using our inhouse instruments.

From start to finish on a site there is a "need to know." Everywhere we improve the site, we need to know the location and elevation. By producing a system that does not depend on direct line of sight for elevation and location, would help revolutionize the construction industry. This would allow us to be considerably more productive and efficient.

Appendix B: Letters from Industry

David Seagren
Charles Pankow Builders, Ltd.

Design- Builder's Perspective

Construction Bottlenecks:

Primary

• Information

As a design-build contractor, the development of architectural and structural documents has the greatest impact on our bottom line. We are ready to commence construction with just the foundation contract documents completed, but usually have to wait. This is the number one source of delay to a project. Can any automation be applied to the architectural and engineering firms in developing design information?

• Information Transfer

Architectural, structural, and MEP document information transfer in expediting the subcontractor shop drawing development and approval process is critical to achieving greater efficiency. For example, can structural drawings be electronically transferred to create and automate reinforcing steel fabrication and placement drawings for precast and cast-in-place construction? Currently these shop drawings may take from 2 to 7 days to draft, depending on complexity, and the specifications usually require an additional 2 to 3 weeks for the structural engineer's approval. Contractors are forced to either proceed without approval or build this time lag into their schedule. For a fast-track project this lag is unacceptable. A significant technology to improve this process a number of years ago was the FAX machine. Another example of a significant bottleneck is the structural steel shop drawings. These may take 6 to 8 weeks to develop and 3 weeks for approval. From the time of subcontract to the steel hitting the jobsite can be 5 to 6 months. Can this task be automated so that shop drawings can be directly extracted from the structural engineer's drawings?

Both of the above examples relate to costs associated with the owner's revenue stream, the cost of financing the project, and the contractor's general conditions. Compressing the schedule for document development and transfer will significantly impact the cost of the project from our perspective.

Beneficial Items:

Minor Software Needs

Performance-based Design Software:

Design tool for performance requirements to be selected by owners (lenders or insurers). Drift (lateral building sway under lateral loading) based?

Code Requirement Software (non-structural)

Input basic initial parameters for conceptual design

3D **Contractor Planning Software**

Site planning, structural erection, material & manpower movement and hoisting locations. Fast and easy input with basic structural elements and equipment preloaded in library. Can this be linked to create rough schedules?

Minor Field Applications

Automate Rebar Cage Fabrication:

Develop portable flexible manufacturing systems to fabricate, onsite, column and beam reinforcing rod cages.

Automate Concrete Placement:

Allow placing boom or pump to place concrete at desired rate and location based on input.

Safety Tag

Develop a worker safety tag which transmits a proximity beacon to receivers on all moving construction equipment to notify the machinery operator through an audible tone of a pending collision. This would prevent accidents caused by lack of visibility and complacency. This type of accident is all too common and costly in our industry

Compression Strength of Fresh Concrete:

Develop a low-cost and accurate instrument that would prevent placement of poor quality material. Most projects will encounter the problem of a low-strength load and the costly ramifications. CPBL applications would include slip-forming construction methods where a low-strength load will halt construction. Similarly, an instrument is needed to accurately measure the water content of concrete transported in ready-mix trucks.

Portable Dust Collector:

Remodel / Build over projects (e.g. shopping mall rennovations) create conditions where contractors must protect store fronts and tenant and anchor merchandise from dust. Drywall dust is the primary culprit.

Water Intrusion Detector:

All buildings leak. Tracing the source of moisture can be an expensive operation as well as a source of ill-will with the owner.

A Note on Most Expensive On-Site Tasks:

The cost of a particular task is highly dependent upon the type of construction and the structural design. The exact same structure at different locations can have significantly different costs associated with different tasks, e.g. setting foundations, and placement and removal of shoring for cast-in-place type construction. Generally speaking, it is important to recognize that labor has the greatest single impact on construction cost.

Highest Safety and Financial Risks:

Fall Protection for employees. Public Safety. Existing structures: protect from damage or settlement.

Recommended NIST Involvement:

- Fund and conduct research where the fragmented construction industry lacks the necessary funding and willingness of owners to pay for it. NIST must keep industry involved during all phases of the research to ensure applicability.

- Technology Transfer: Provide means and methods to introduce new technology and overcome cost barriers.