NIST GCR 16-005

Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing

Advanced Robotics and Automation

August 2016

Prepared for—

Economic Analysis Office
National Institute of Standards and Technology
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Gaithersburg, MD 20899

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This publication is available free of charge from:
http://dx.doi.org/10.6028/NIST.GCR.16-005

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

Acknowledgements

Many contributed to the preparation of this report, and we wish to acknowledge in particular the private companies, industry associations, research institutes, universities, and government agencies whose experts contributed data and insights underlying the analysis herein.

In addition to this study's lead authors, significant contributors included Luca Alessandro Remotti of the Joint Institute for Innovation Policy (formerly of Intrasoft S.A.), Raimund Broechler of Intrasoft S.A., and Jeff Cope of RTI's Innovation Advisors.

We would also like to acknowledge the advice and subject matter expertise contributed by NIST economic and scientific staff. Specifically, we are especially grateful for the contributions of

- Gary Anderson of NIST's Economic Analysis Office,
- Timothy Burns of NIST's Applied and Computational Mathematics Division,
- Stephen Campbell of NIST's Economic Analysis Office,
- Heather Evan of NIST's Program Coordination Office,
- Simon Frechette of NIST's Systems Integration Division,
- Albert Jones of NIST's Systems Integration Division,
- James Liddle of NIST's Center for Nanoscale Science and Technology,
- Eric Lin of NIST's Materials Science and Engineering Division,
- Richard Ricker of NIST's Materials Measurement Science Division,
- Christopher Soles of NIST's Materials Science and Engineering Division,
- Albert Wavering of NIST's Intelligent Systems Division, and
- Paul Zielinski of NIST's Technology Partnerships Office.

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This publication was produced as part of contract GS10F0097L with the National Institute of Standards and Technology. The contents of this publication do not necessarily reflect the views or policies of the National Institute of Standards and Technology or the US Government.

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U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Under Secretary of Commerce for Standards and Technology and Director

Contents

Appendixes

Figures

Tables

Executive Summary

Advanced robotics and automation have been discussed as potential game-changing technologies for strengthening the U.S. manufacturing sector, particularly for small and medium-sized manufacturers (SMEs). Advanced robotics can help to decrease production costs as well as offer greater flexibility to manufacturers to respond to changing market conditions and consumer preferences. Next-generation robots could be mobile and autonomous in their environment, with the ability to operate in unstructured environments free from the physical cages that have surrounded traditional industrial robots for decades and to collaborate safely with humans while doing so.[1]

Many companies face barriers in adopting robotics technologies because of robotics' hard and soft costs and the associated learning curve. Missing from the marketplace are standards, technology platforms, and other fundamental pieces of technology, making technology adoption more costly and difficult than it needs to be. Because firms cannot profit from developing these public-good technologies, they do not develop them, which in turn discourages innovation and undermines American competitiveness. Public-sector support of relevant technology infrastructure will help lessen, if not outright, remove many barriers.

Economic benefits associated with meeting technology infrastructure needs in robotics and automation could approach $40 billion per year. This represents, on average, a 5% reduction in the shop floor cost of production. This economic

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[1] Many of these concepts were outlined in *A Roadmap for U.S. Robotics—From Internet to Robotics* (Robotics-VO, 2009), which led to the National Robotics Initiative, and the successor report (Robotics-VO, 2013).

benefit is largely driven by material and labor savings, which are partially offset by an increase in capital investment.

We consider this estimate conservative because it does not capture several hard–to-measure benefits, such as improved product quality and accelerated market transformation. It is also based on recent (and not projected) industry data.

ES.1 SCOPE OF THE ANALYSIS

This study is a collaborative effort among multiple units within the National Institute of Standards and Technology (NIST) to determine technology infrastructure needs to support advanced manufacturing. It presents findings of an economic analysis of the technology infrastructure, which includes standards, measurement, and general-purpose technology, and the role of this infrastructure in the efficient development and adoption of advanced robotics and automation in the United States.

There is currently a lack of understanding of what is inhibiting the development and adoption of robotics technology. If barriers to adoption do exist, the question is *What role can government play in mitigating these barriers and accelerating the penetration of robotics technology in the U.S. manufacturing sector?* By addressing this question, this study represents a departure from most existing studies of robotics because it specifically focuses on needed technology infrastructure, which, because of its public good characteristics, is in the purview of NIST.

The objectives of this strategic planning study were to

- identify current and emerging trends related to robotics and automation, with specific focus on applications in manufacturing;
- identify technology infrastructure needs to support the development and adoption of robotics and automation technology;
- document the challenges and barriers that inhibit the development of technology infrastructure;
- estimate the economic benefit of meeting these technology infrastructure needs; and
- assess potential roles for NIST in meeting technology infrastructure needs.

Ultimately, the purpose of the study is to provide NIST with information on industries' technology infrastructure needs to help inform NIST's strategic planning.

ES.2 ANALYSIS APPROACH

The methodology includes the collection and analysis of qualitative and quantitative data from primary and secondary sources. To ensure that a variety of perspectives are accounted for, RTI interviewed a cross-section of 84 experts from industry associations and research centers, developers of robotic systems and component technologies, system integrators, and end users of robotics within the manufacturing sector. We also had informal conversations with individuals at conferences and industry events, which contributed to the findings in this report.

We approached interviewees with a set of capabilities, which, through our first phase of interviews[2], we found to be of the utmost importance to members of the manufacturing value chain:

- Safe human-robot interaction (HRI)
- Sensing and perception for unstructured (or less-structured) environments
- Objective, low-cost performance characterization
- Interoperability and modularity
- Intuitive interfaces
- Modeling and simulation

These six capabilities were consistently identified by manufacturers as needed for the full and efficient application of advanced robotics and automation technology.

Quantitative information from interviews about the impact that these capabilities and the underlying technology infrastructure would have formed the basis of our economic models that estimate the economic benefits that enhanced technology infrastructure would have on the U.S. manufacturing sector.

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[2] Phase 1 interviews occurred in 2014. Interviews lasted between 30 and 60 minutes and were conducted by telephone. The interviews were unstructured to offer the greatest flexibility in eliciting insights about the current status and future opportunities of technologies and applications. In-depth interviews were particularly effective for data collection given the nuanced topics of interest.

Other key parameters in our models were derived from publicly available data on the manufacturing sector.

ES.3 ANALYSIS OF TECHNOLOGY INFRASTRUCTURE NEEDS

Table ES-1 summarizes the technology infrastructure needed to support robotics and automation capabilities along with the associated potential benefits and impacts resulting from an enhanced technology infrastructure. These benefits underpin the economic impacts estimated as part of the study.

Table ES-1. Required Capabilities for the Application of Advanced Robotics in Manufacturing, Associated Infratechnology Needs, and Benefits

Industry Capabilities	Examples of Infratechnology to Help Meet Needs	Potential Benefits and Impacts
Safe human-robot interaction (HRI) Universal standards for developers of robotics technologies and the application of these technologies in manufacturing settings with robots working in close proximity to people (see more below on sensing/perception for unstructured environments, relevant for intuitive HRI)	• Test protocols, objective scientific and engineering data, reference databases, and other technical inputs into standards for safe HRI (power/force-limiting, speed/separation monitoring, hand-guided operation, safety-rated monitored stop)	• More flexible, smaller-footprint production lines • New and creative use cases of robots working in close proximity and in collaboration with people • Lower integration costs • Improved safety • Reduced market risk for developers • Reduced liability for end users • Increased adoption of collaborative robots
Sensing and perception for unstructured (or less-structured) environments Improved perception (and the ability to plan and re-plan the robot's actions based on what it "sees" and "knows") gives a robot greater autonomy, lessening its demand that its work environment meet stringent tolerances	• Sensor registration and calibration • Performance characterization (benchmarks, testbeds, and technical inputs to standards to characterize the performance of systems, subsystems, and components) • Sensing/perception engines/architectures • Proof-of-concept robotics applications of knowledge representation and reasoning	• Lower integration costs associated with accommodating tolerances • Flexible navigation of unstructured or less-structured environments • More flexible plant layouts • Improved safety • Optimized robot motions • Data streams to calibrate simulation models
Objective, low-cost performance characterization Making it easier for robotics users to know what they are buying and for developers and suppliers to show what their systems do	• Common performance metrics, objective data, testbeds, test methods, and benchmarks to characterize the performance attributes of advanced systems, subsystems, and components	• Reduced uncertainty • Improved understanding of new technologies • Increased adoption of robotics by SMEs

(continued)

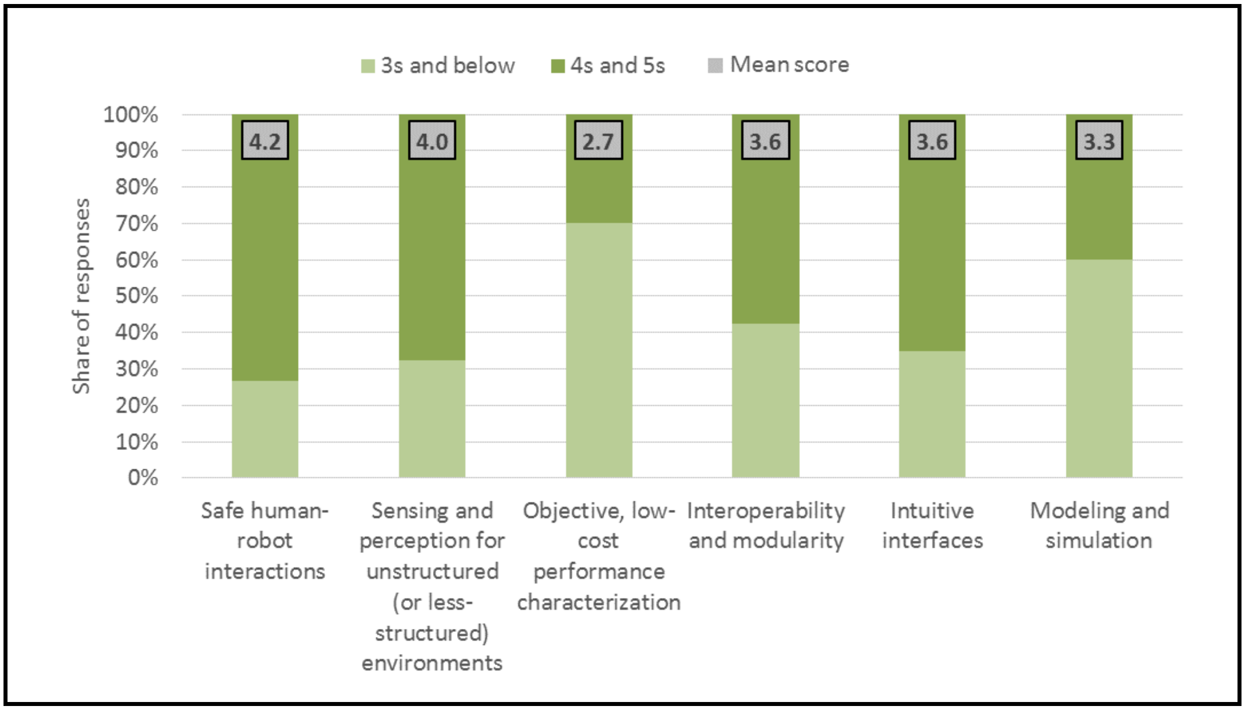
Table ES-1. Required Capabilities for the Application of Advanced Robotics in Manufacturing, Associated Infratechnology Needs, and Benefits (continued)

Industry Capabilities	Examples of Infratechnology to Help Meet Needs	Potential Benefits and Impacts
Interoperability and modularity Plug-and-play for system components, enabled by standards for physical and electronic interfaces and software interfaces or translators	• Objective technical inputs into the standard-setting process: scientific and engineering data, benchmarks, testbeds, objective third-party testing of candidate technologies and configurations	• Plug-and-play functionality • Reduced integration costs (physical and software interfaces) • Modular development of systems • Increased adaptability of robotic systems • Scalable, reconfigurable, and reusable robotic systems • Reduced retooling costs • Increased adoption in industries with small production runs
Intuitive interfaces Enabling rapid programming and training without specialized skills	• Protocols to simplify the programming, training, and rapid re-tasking of robots • Standard programming language for industrial robotics analogous to SQL or HTML	• Simplified programming • Reduced setup time and setup costs • Enables individuals without specialized training to commission a robotic system
Modeling and simulation Virtual factory floor allowing modeling and simulation, calibrated based on real-time data feed from robots, machine tools, sensors, and control systems on the floor	• Robust, open, real-time operating system on the factory floor • Reference models, modeling frameworks to fully integrate robots into models of the manufacturing environment and enable robust simulation/prediction	• Control of processes from central dashboard • Improved prediction • Adjustments can be optimized • Reduced delay and work stoppage • Software reconfigurable factory floor • Reduced retooling costs • Improved “as-built” documentation • Using robot teaching to refine simulation models

To provide a barometer for NIST in terms of how it might be able to accelerate the development and adoption of robotics technology most effectively, interviewees were asked to characterize the importance of each of the six capabilities in Table ES-1 and corresponding infratechnologies. Safe HRI, sensing and perception for unstructured environments, intuitive interfaces, and interoperability and modularity appear to be the most important needs, whereas the interviewees evaluated modeling and simulation and objective, low-cost performance characterization as noticeably less important.

Figure ES-1 summarizes the responses about the level of importance (measured as 1 to 5, where 1 represents the least important and 5 represents the most important) by capability.

Figure ES-1. Importance of Capabilities/Needs and Corresponding Infratechnology Needs



Note: The level of importance of each capability is measured on a scale from 1 to 5, where 1 represents the least important and 5 represents the most important.

The percentage of interviewees who responded with a 4 or 5 are in darker shades, and the percentage of interviewees who responded with a 3 or below are in lighter shades. The average importance score is overlaid in the gray boxes.

As reflected in the figure, the majority of interviewees evaluated safe HRI, sensing and perception for unstructured environments, intuitive interfaces, and interoperability and modularity as being important.[3] Modeling and simulation and objective, low-cost performance characterization are noticeably less important.

The following subsections discuss the needs and barriers to development within each capability area.

ES.3.1 Safe Human-Robot Interaction

Safe HRI is arguably the most important and potentially transformative of the six needed capabilities for robotics technology. The development and adoption of safe human-

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[3] That is, they evaluated the importance of the capability with a 4 or a 5.

robot technology is inhibited by several barriers to innovation (sources of market failure) such as the broad scope of commercial applications that is beyond the reach of any individual firm, technical risk, market risk due to safety issues and cultural acceptance, and difficulty in bringing together component technologies that are necessary for various approaches to safe HRI.

Enhanced infratechnologies needed to enable safe HRI include standardized risk assessment tools, test methods, and new taxonomies and paradigms of safe HRI. Another industry need mentioned was public sector coordination with major players that have influence on robot safety standards, among other things.

ES.3.2 Sensing and Perception for Unstructured Environments

Sensing and perception for unstructured environments is one of the most important capabilities because it would allow robots to navigate unstructured and/or semi-structured environments, which would enable new applications and more flexible deployment of robots in the factory environment. Improved sensing and perception would also directly support safe HRI.

The development and adoption of sensing and perception technology are inhibited by several barriers to innovation (sources of market failure) such as the difficulty in bringing component technologies together, the scope of commercial applications being broader than the market strategy of any one firm, and the long and uncertain lag between R&D investments and returns.

There appears to be a potential role for the public sector, perhaps through NIST, to play a role in enhancing infratechnologies by conducting research on new sensing technologies, improving interoperability in support of sensing and perception, and working on market demonstration efforts. RTI also offers the idea of closer coordination and collaboration with other organizations as a vehicle for lessening innovation barriers, based on many comments from interviewees.

ES.3.3 Intuitive Interfaces

Intuitive interfaces for interacting with robots is an important industry need, especially considering the lack of skilled workers and technical knowledge that many companies described as a barrier to adoption. Intuitive methods of programming and teaching robots such as graphical user interfaces (GUIs) would make robots more accessible to all manufacturers, specifically SMEs, which tend to have a smaller pool of technical knowledge to tap into.

Comparisons were drawn between the need for intuitive robot interfaces and other languages such as SQL and M-code.[4] These comparisons may indicate that although a GUI would be beneficial, the most important aspect of intuitive interfaces may simply be standardizing robot programming across the industry. This would prevent individuals from having to learn multiple robot programming languages and would allow a set of work instructions to be executed by any robot regardless of supplier.

The development and adoption of intuitive interfaces is inhibited by several barriers to innovation (sources of market failure) such as the risk that R&D outcomes, although technically sufficient, will gain insufficient market acceptance and cause difficulties in bringing together component technologies.

Industry initiatives toward this end, such as Robot Operating System (ROS) and ROS-Industrial (ROS-I), are under way. NIST is working with this effort and is using ROS-I in ongoing projects. Industry pointed out that there is value in NIST research activities that dovetail and complement existing efforts.

ES.3.4 Interoperability and Modularity

Interoperability and modularity can support other capabilities such as sensing and perception and intuitive interfaces. Improved interoperability and modularity of robotics technology alleviates the difficulty of bringing together component technologies, which is a common barrier to innovation in this industry. Plug-and-play interoperability can be achieved by standardizing physical interfaces, electronic interfaces, and software interfaces, or translators.

Interoperability and modularity is inhibited by several barriers to innovation (sources of market failure) such as positive network externalities, difficulties in bringing together

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[4] M-code is a subset of machine functions in G-code, a commonly used numerical control programming language.

component technologies such as physical interfaces for hardware or communications protocols for software, and industry structure.

Industry indicated that research-based standardization efforts would help accelerate the development and adoption of interoperable and modular technologies. Industry also indicated the importance of coordination among robot manufacturers, end users, industry associations, and professional groups, and the need for a neutral, third-party coordinator. Horizontal and vertical interoperability are needed.

ES.3.5 Modeling and Simulation

Modeling and simulation appeared to be somewhat less important relative to some of the other capabilities. However, modeling and simulation tools for risk assessments could enable the more efficient deployment of collaborative robots.

Simulation could significantly reduce the time and cost involved in changing between production lines if the factory floor was software reconfigurable. Other benefits of simulation include a better understanding of tool paths and documenting as-built products compared with their digital counterparts. Simulation models could also be used to convert robot training and teaching on the factory floor into transferable knowledge that can be applied to different situations in the future.

Modeling and simulation is inhibited by two barriers to innovation (sources of market failure): technical risk and the difficulty of bringing together component technologies.

The most important future application of simulation appears to be for supporting safe HRI through risk assessment and quantification of relevant dimensions of HRI. Key infratechnologies that are needed include libraries, reference data, and reference models. There are also some industry needs around measuring the fidelity of simulation models.

ES.3.6 Objective, Low-Cost Performance Characterization

Objective, low-cost performance characterization would address informational asymmetries between developers and end users of robots. The importance of this capability depends on the unique context and situations of each end user.

If objective, low-cost performance characterization were to be standardized, it could stimulate innovation by giving users a common way to communicate needs to developers and by giving developers a common target for focusing R&D efforts. However, interviewees suggested that a public role may be limited here because industry would need to lead any measurement standards. Generally, industry has to be involved in developing standards that it will use, but the importance of industry involvement is particularly strong in this case because performance measures are directly used to market robotics technologies.

Perhaps the single greatest need for performance characterization would be in the area of measurement supporting safe HRI.

ES.4 SUMMARY OF ECONOMIC IMPACTS

The deployment of robots in the U.S. manufacturing sector to date has largely been in automotive manufacturing. If critical enabling infratechnologies were in place, advanced capabilities, such as safe HRI and enhanced sensing and perception, would be possible. The existence of advanced capabilities (and associated infratechnologies), as outlined in this report, would stimulate industry investment in robotics technology and lead to the realization of an estimated $40.4 billion in net economic savings of U.S. manufacturers per year, based on recent industry data.

Table ES-2 shows the average percentage change in capital, labor, energy, and materials (KLEM) due to having technology infrastructure needs met. End users indicated that labor costs could be reduced by an average of 18%, and materials costs could be reduced by 8%. These cost savings could be achieved by a net increase in capital expenditures of 22%. The economic impact of the increased adoption of robotics and automation on energy consumption would be negligible.

Table ES-2. Percentage Change in Factor Inputs Due to Meeting Industry Technology Infrastructure Needs for Robotics and Automation

Factor Input	Mean Impact of Meeting Industry Needs
K: Capital	+22%
L: Labor	−18%
E: Energy	+1%
M: Materials	−8%

Table ES-3. Economic Impact Summary Table

	Industry Data, 2013		Cost Impacts, Billions					
	Sales	**Shop Floor KLEM National Factor Expenditure**	**K: Capital**	**L: Labor**	**E: Energy**	**M: Materials**	**Total**	**Percentage Impact**
Total	$2.13 trillion	$759 billion	+$11.4	−$22.1	−$0.4	−$29.3	−$40.4	−5.3%

Changes in factor inputs were then scaled to the national level to estimate the economic impacts associated with enhanced infratechnology. Table ES-3 shows that national economic impacts are estimated to be approximately $40.4 billion.

The aggregate national economic impacts represent, on average, a 5% reduction in national factor expenditures. Materials savings, although a smaller percentage impact than labor savings, accounts for the largest share of savings because it accounts for approximately three-fifths of manufacturing production costs.

Figure ES-2 shows the distribution of impacts apportioned to each of the six capabilities. The distribution of impacts reflects the importance scores provided by end users. Intuitive interfaces, safe HRI, and sensing and perception all have impacts greater than $7 billion. These are followed by interoperability and modularity as well as modeling and simulation, with $6.6 billion and $6.3 billion in cost impacts, respectively. Reflecting its lower overall importance score, objective, low-cost performance characterization has the smallest impact of all capabilities with $5.4 billion.[5]

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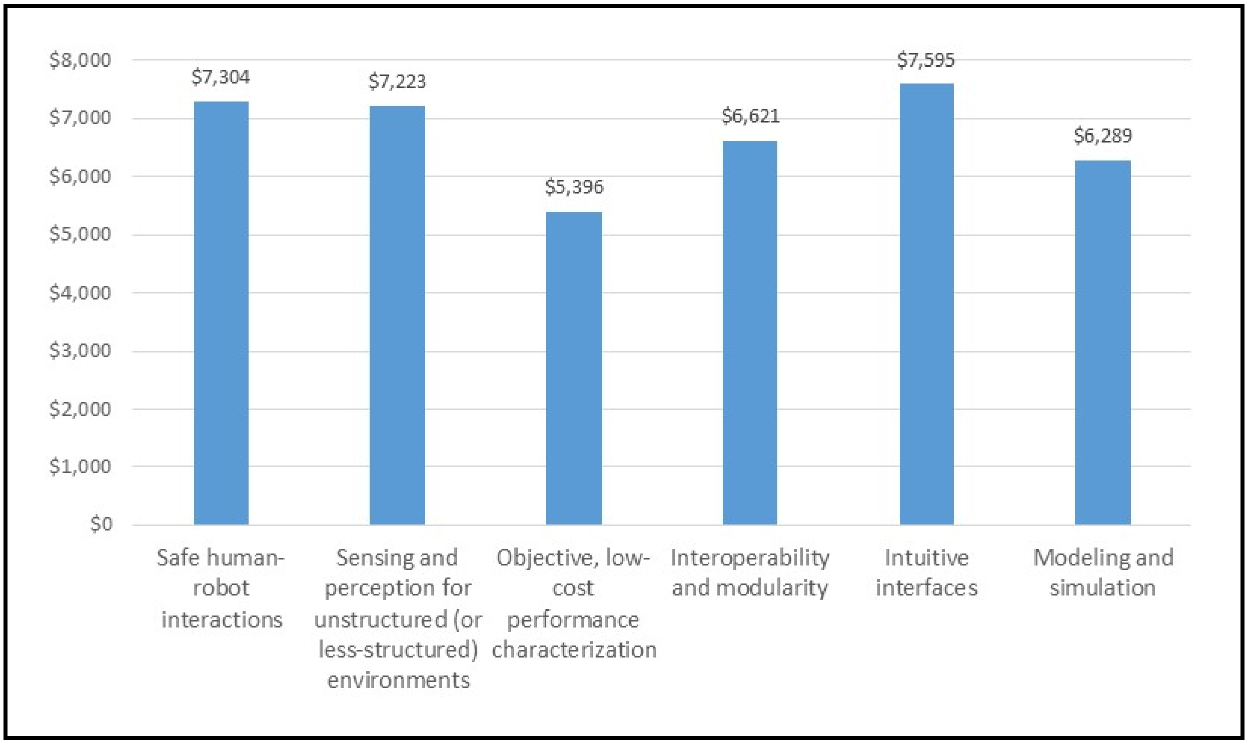
[5] There are often strong complementarities or “interaction effects” between capabilities that we were not able to quantify.

Figure ES-2. Total Cost Impact, by Capability (Millions of 2013 US$)



Note that the economic impact estimates presented are conservative in that they focus on reductions in manufacturers' production cost that would result from meeting the identified technology infrastructure needs. Not included in the economic impact calculations is the economic value associated with reduced R&D costs, improved product attributes, increased sales, or accelerating the introduction of new products to the market.

1 Overview of Robotics and Automation

Advanced robotics and automation have been discussed as potential game-changing technologies for strengthening the U.S. manufacturing sector, particularly for small and medium-sized manufacturers (hereafter, small and medium-sized enterprises [SMEs]). Increased development and adoption of this technology could also be an important competitive advantage for the United States, enabling U.S. manufacturers to maintain and improve international competitiveness through enhanced labor productivity, production efficiency, and quality. Furthermore, advanced robotics can offer greater flexibility to manufacturers to respond to changing market conditions and consumer preferences.

In calling for an Advanced Manufacturing Initiative, the President's Council of Advisors on Science and Technology (PCAST) highlighted advanced robotics as a technology area where public-private investment could support advances in manufacturing (PCAST, 2011, p. 28).[6]

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[6] In its July 2012 report, PCAST called for increased research and development funding in 11 cross-cutting technology areas, one of which was industrial robotics (PCAST, 2012). In its 2013 annual report, the President's Council of Economic Advisers emphasized again the importance of robotics technology: "The Administration also has proposed initiatives to replenish the technology pipeline, by increasing funding for advanced manufacturing R&D. Despite tightening budgets, the Administration has emphasized the importance of funding industrially relevant, advanced manufacturing technologies such as advanced materials, smart manufacturing, and robotics" (Council of Economic Advisers, 2013, p. 234).

Part of the president's Advanced Manufacturing Initiative was to establish the National Robotics Initiative, whose goal is to accelerate the development and use of robots in the United States.[7]

Next-generation robots could be mobile and autonomous in their environment, with the ability to operate in unstructured and semi-structured environments and to collaborate safely with humans while doing so. These next-generation robots could achieve all of these things without the restrictive and space-inefficient physical cages that have surrounded traditional industrial robots—the large, powerful, fast-moving robots that operate in safe, guarded space, cordoned off from factory workers—for decades.[8] In fact, one of the objectives of the National Robotics Initiative is "the realization of such co-robots working in symbiotic relationships with human partners" (NSF, n.d.). Furthermore, these objectives could be achieved without using esoteric programming languages that require PhD-level training. Ultimately, next-generation robots will be easier to integrate into manufacturing production lines.

Some contend that "a dramatic takeoff in advanced robots is imminent. … [G]rowth in the installed base of robotics will accelerate to around 10 percent annually during the next decade" (Sirkin, Zinser, & Rose, 2015, p. 6).

Experts interviewed for this study indicated that the collaborative robotics market is expected to grow substantially within the next few years. One forecast was that the market for collaborative robots will grow in excess of 100% each year for the next few years, regardless of the National Institute of Standards and Technology's (NIST's) actions, although enhanced technology infrastructure—the broad base of quasi-public technologies and technical knowledge that supports firms', universities', and laboratories' research and

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[7] Agencies involved in this initiative include the National Science Foundation (NSF), the National Aeronautics and Space Administration, the National Institutes of Health, the U.S. Department of Agriculture, and the U.S. Department of Defense. See NSF (n.d.). Refer to https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503641 for additional details.

[8] Many of these concepts were outlined in *A Roadmap for U.S. Robotics—From Internet to Robotics* (Robotics-VO, 2009), which helped lead to the National Robotics Initiative, and the successor report in 2013.

development (R&D) and production of improved and entirely new products and processes—could have a multiplier effect on economic growth.

Another interviewee echoed a common theme that the growth of collaborative robotics will have an impact on for SMEs: “All of a sudden every mom and pop manufacturer can look at robotics and have it not be a stretch… The impact of less expensive, more flexible robots will be seen especially among small-and medium-sized fabricators. Each fabricator may only adopt 1 or 2 robots at a time but there are hundreds of thousands of [fabricators].”

Robots are an important component of more flexible manufacturing systems. Intelligent automation could build robots’ capabilities to increase autonomy and flexibility to enable manufacturers to respond efficiently to customers’ needs and desires. To stay competitive in today’s marketplace, manufacturers must maintain flexibility in their production systems because products have shorter life cycles and consumers are demanding a greater variety of goods (PricewaterhouseCoopers, 2014, p. 1).

Major advances could provide broad-based innovations benefiting multiple industries, such as those provided by computer-aided design and computer-aided manufacturing, total quality management, and just-in-time manufacturing. However, advances in developing and commercializing robotics technologies are happening more slowly in the United States than in other industrialized nations such as the European Union (EU), Japan, China, and South Korea because of an underinvestment by private companies in robotics R&D. In fact, some claim that the underinvestment is not specific to the private sector; despite a handful of U.S. initiatives supporting robotics, the public sector has also underinvested in relevant innovations specifically compared with EU initiatives (MIT Committee to Evaluate the Innovation Deficit, 2015).

Furthermore, public-private investments in advancing robotics technology could help U.S. manufacturers compete in the global economy by enabling reductions in production costs, improvements in labor productivity, improvements in product quality, and reductions in time to market. These improvements would support a national policy imperative of reinvigorating the U.S. manufacturing sector.

Given that the market for robotics and automation is characterized by several sources of market failure, the public sector can help the market achieve a more socially efficient use of its resources. This report, prepared for NIST's Economic Analysis Office, explores technology infrastructure needs that NIST can help meet to support and enhance the development and adoption of robotics and automation in the U.S. manufacturing sector.

1.1 DEFINITION OF TECHNOLOGY INFRASTRUCTURE

Technology infrastructure is the broad base of public and quasi-public technologies[9] and technical knowledge that support the R&D and production efforts of firms, universities, and laboratories, as well as the development and adoption of improved and entirely new products, processes, and services (e.g., higher quality, more effective, more efficient, more productive).

Technology infrastructure supports and accelerates enhancements in advanced manufacturing capabilities. Specifically for robotics and automation, enhanced technology infrastructure could have the ability to enable capabilities such as

- safe human-robot interaction (HRI);
- sensing and perception for unstructured (or less-structured) environments;
- objective, low-cost performance characterization;
- interoperability and modularity;
- intuitive interfaces; and
- modeling and simulation.

Technology infrastructure includes infratechnologies and technology platforms (see Table 1-1). It is often the case that the public sector supports the majority of technology infrastructure research because of its public-good content (Tassey, 2008).

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[9] Technologies with varying degrees of public good content.

Table 1-1. Definitions of Key Concepts

Term	Definition	Examples
Technology infrastructure	The broad base of quasi-public technologies and technical knowledge that support the R&D and production efforts of firms, universities, and laboratories, as well as the development and adoption of improved products, processes, and services.	• Infratechnologies • Technology platforms
Infratechnologies	A varied set of "technical tools" that include measurement and test methods, artifacts such as standard reference materials that allow these methods to be used efficiently, scientific and engineering databases, process models, and the technical basis for physical and functional interfaces between components of systems technologies such as factory automation and communications.	• Standard reference materials • Process models • Techniques for process and quality control • Calibration services • Traceability of measurements and test methods • Benchmarks and testbeds for characterizing a new technology's expected performance under realistic conditions • Objective characterization of performance attributes of component technologies • Reference datasets of common human poses
Technology platforms	Precompetitive proofs of concept that demonstrate the potential commercial viability of a new or improved product, process, or service. A characteristic of a technology platform is that it will often be foundational to multiple products and processes, generally from multiple firms.	• Bell Labs' transistor proof-of-concept using solid state physics principles (Tassey, 2008) • Prototype networks such as ARPANET and NSFNET that led to the Internet (Tassey, 2008) • Open-source software such as Robot Operating System (ROS), ROS-Industrial, and OpenCV • Standard perception engines for sense data types and sense data fusion (euRobotics, 2014)
Proprietary technologies	Commercialized products, processes, and services that may be derivatives of technology platforms and have been influenced by infratechnologies. Some proprietary technologies may have de facto quasi–public good characteristics, but they are not in the scope of this analysis.	• Industrial robots • Collaborative robots • Machine vision systems

1.1.1 Infratechnologies

Historically, NIST has focused resources on this aspect of technology infrastructure. Infratechnologies are a varied set of “technical tools” that include measurement and test methods, artifacts such as standard reference materials that allow these methods to be used efficiently, scientific and engineering databases, process models, and the technical basis for physical and functional interfaces between components of systems technologies such as robotics and automation technologies. As written in Tassey (2008), “[c]ollectively they constitute a diverse technical infrastructure, various types of which are applied at each stage of economic activity.” New infratechnologies often replace less efficient forms of infratechnology that support current standards (Tassey, 2008).

Infratechnologies influence the development of technology platforms and proprietary technologies. They also support efficient R&D, production, and market transactions such as complying with customer requirements and regulations.

Infratechnologies provide the technical basis for standards that are set using consensus standard-setting processes that are usually led by industry organizations. Their benefits include full disclosure of information, reduced uncertainty regarding product attributes, and an overall improved level of trust that helps to reduce market transaction costs.

The provision of infratechnologies requires a combination of industry and government investment because infratechnologies have substantial public good content (Antonelli & Link, 2015). Some industries depend on hundreds of distinct infratechnologies and associated standards. Furthermore, a particular infratechnology may have spillover benefits for many industries.

1.1.2 Technology Platforms

Technology platforms are precompetitive proofs of concept that demonstrate the potential commercial viability of a new or improved product, process, or service. These fundamental technical concepts originate from basic science research and can even be enabled by measurement infratechnologies (Link & Scott, 2010).

A characteristic of a technology platform is that it will often be foundational to multiple products and processes, the scope of which is typically broader than the business model of any one firm. Therefore, no firm is able to fully appropriate the benefits of investing in the development of a technology platform, so achieving the socially optimal level of investment will generally require additional public investment.

1.2 PROPRIETARY TECHNOLOGIES

Proprietary technologies are commercialized products, processes, and services that may be derivatives of technology platforms and have been influenced by infratechnologies. Generally, firm investments in proprietary technology fall under the category of R&D spending. Proprietary technologies that are relatively ubiquitous may have quasi–public good characteristics though they are almost exclusively funded and developed by private-sector firms. These technologies are in-scope to the extent that the technology infrastructure on which we focus enables their development and adoption.

1.3 SCOPE OF THE ANALYSIS

This report identifies gaps in technology infrastructure inhibiting the development and adoption of advanced robotics and automation in the U.S. manufacturing sector, and it quantifies the prospective economic benefits associated with addressing those gaps. The report also outlines specific potential opportunities for NIST to accelerate the development and adoption of critical technology infrastructure.

The research supporting this report was informed by primary data collection that consisted of interviews with experts in the robotics and automation value chain.[10] It also was informed through a secondary collection of industry information.

To ensure that a variety of perspectives are accounted for, RTI spoke with a cross-section of experts in various stakeholder groups. We interviewed 84 individuals from industry associations and research centers (hereafter, observers); manufacturers of robotic systems, robotic component technologies including hardware and software, and related

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[10] The value chain concept is a broader concept than the supply chain. Value chains include any stakeholders that add value to the end product or process, whether through providing goods, services, knowledge, coordination, and so on.

automation technologies (hereafter, developers); system integrators; and end users of robotics within the manufacturing sector. We specifically focused on end users in automotive manufacturing, aerospace manufacturing, electronics manufacturing, metal product manufacturing, process-oriented manufacturing, and other discrete parts manufacturing.

1.4 BARRIERS TO DEVELOPMENT AND ADOPTION

A motivating factor for this study is that private investments in innovation and diffusion of new technologies typically generate social value in excess of their private returns. As a result, some socially productive technology investments are not undertaken because private firms do not perceive the research as profitable.[11]

The rate and extent of development of robotics technologies with the needed capabilities, as outlined in Section 1.4, and the rate and extent of their adoption in advanced manufacturing applications, will depend on the parallel development and diffusion of technology infrastructure that is generally underprovided by the market. This resulting market failure—the failure of the market to allocate a socially optimal level of infrastructure—provides an opportunity to improve the efficiency of economic outcomes through public investments in technology infrastructure.

Table 1-2 lists eight barriers to investment identified in the literature.[12] These barriers that bring about market failure are present for robotics and can be expected to result in a reduction of overall economic welfare unless they are addressed through public support or other means. Each barrier describes general R&D market failures, and some barriers are specific to technology infrastructure.

Advanced robotics, like any emerging technology, has yet to exploit fully all relevant scientific knowledge. The probability of

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[11] The private rate of return is less than what is required (the private hurdle rate), even though the social rate of return exceeds that required by society (the social hurdle rate).

[12] The taxonomy of barriers presented here draws insight from Link and Scott (2010) and Jaffe (2005).

Table 1-2. Barriers to Developing and Adopting New Technology That Bring about Market Failure

Barrier	General R&D Market Failures	Market Failures with Regard to Technology Infrastructure
Inability to appropriate all social benefits, such as positive network externalities	●	●
Scope of commercial applications is broader than the market strategy of any one firm	●	●
Risk that R&D outcomes will be technically insufficient (technical risk)	●	
Risk that R&D outcomes, although technically sufficient, will not be received well by the market, thereby providing an unacceptable return on investment (commercial or market risk)	●	
Long and uncertain lag between R&D investments and returns	●	
Asymmetric information between developers and adopters of new technology	●	●
Difficulties in bringing together component technologies from different industry segments	●	●
Industry structure, such as network externalities, presenting market-entry barriers to new technology	●	

developing any commercially successful product is low, but increasing the probability of technical success through using robotics technology will certainly increase the probability of commercial success. As we argue in this report, firms, and SMEs in particular, face a barrier to adopting robotics technology because of the cost of robotics technology and the associated learning curve. Public sector support of relevant technology platforms will help to lessen if not outright remove this barrier.[13]

Although it is difficult to rival the clarity of the 1950s Bell Labs demonstration of the concept of the transistor—a classic example of a technology platform—perhaps a parallel example for advanced robotics would be a standard perception engine that assimilates various sensor inputs and then the platform reasons what to do (how, for instance, to incorporate sensory

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[13] Tassey (2010) provides an excellent discussion of the roles of infratechnologies and technology platforms in innovation.

input into motion planning for moving an arm or grasping an object). Adequate development of technology platforms could help industry begin to bridge the gap from the science of knowledge representation and reasoning (KR&R) to commercially viable advanced robotics technologies. For example, euRobotics AISBL (2014) suggests that KR&R, which is a subfield of artificial intelligence, may have unexplored potential for robot autonomy.

Open-source efforts also play an important role as technology platforms for advanced robotics. NIST can contribute to and help accelerate such efforts. OpenCV and Robot Operating System (ROS)/ROS-Industrial (ROS-I) represent two important open-source efforts in robotics:

- OpenCV is an open-source computer vision and machine learning software library with more than 47,000 people in the user community and more than 7 million downloads. Well-established companies and startups alike are using OpenCV computing infrastructure and algorithms for sophisticated machine vision applications.[14]
- ROS is a modular collection of tools, libraries, and conventions that simplify robot programming in a way that can be applied across different robot systems. ROS-I extends the capabilities of ROS to the manufacturing environment. ROS and ROS-I are both open-source projects.[15]

Private investment in R&D to bring forth a new or advanced technology depends on the expectation that the technology will find a market. This requires that manufacturers—the end users of advanced robotic systems—can hire skilled workers who are ready to program, maintain, and repair those systems and to work alongside them. Adequate expected return on these R&D investments also depends on standards for safety, performance, and interoperability to allow emerging technologies to be exploited to their fullest potential.

The existing regulatory framework (e.g., Occupational Safety and Health Administration regulations) should reference and incorporate new standards—standards for safety, performance, and interoperability—to experience the full benefits of advanced

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[14] http://opencv.org/

[15] http://rosindustrial.org/

robotics technology. This framework is starting to emerge with recent Robotic Industries Association (RIA) safety standards but is far from complete. Safety standards, for instance, must take into account the capabilities of new technologies to allow safe applications that fully exploit the technologies' potential. These standards can then be used to implement safety controls clearly and consistently to manage risks for robot integrators and end users. Performance standards and interoperability are needed to reduce the cost of developing and using advanced robotic systems and to reduce transaction costs (and technical risk) arising from information asymmetries among developers and end users. Reducing the cost of integrating new technologies into manufacturing processes will increase the expected return and thus the level of future investment in development and commercialization, as well as the pace of technology adoption by manufacturers.

Cultural acceptance will require confidence that individuals will not be harmed by using the technology in accordance with applicable safety standards. Beyond being safe, the interaction with robots must be natural and intuitive if the technology is to gain widespread acceptance. How best to achieve this is very much an open question among developers of robots. One developer put the question this way: "What is the right metaphor for robots interacting with people?"[16]

1.5 NEEDED CAPABILITIES AND TECHNOLOGY INFRASTRUCTURE

As described previously, advanced robotic systems are in many ways becoming more flexible and versatile than traditional industrial robots. However, a lack of critical technology infrastructure inhibits the development and adoption of advanced robotics.

RTI has identified six broadly defined industry needs, or capabilities, as being necessary to fully and efficiently apply advanced robotics and automation technology in manufacturing industries (Table 1-3). Additionally, examples of underlying

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[16] Drawing an analogy to the question of what robots working side by side with people ought to look like, this observer pointed out, "Your car does not pretend to be a horse."

technology infrastructure to help meet the needed capabilities are outlined.

The six advanced capabilities in Table 1-3 are discussed at length in Sections 5–10 with reference to barriers to innovation that bring about market failure, potential impacts of meeting technology infrastructure needs, and potential roles for NIST. In these discussions, references are made to specific comments by interviewees.

Table 1-3. Required Capabilities for the Application of Advanced Robotics in Manufacturing and Associated Infratechnology Needs

Industry Capabilities	Examples of Infratechnology to Help Meet Needs
Safe human-robot interaction (HRI) Universal standards for developers of robotics technologies and the application of these technologies in manufacturing settings with robots working in close proximity to people (see more below on sensing/perception for unstructured environments, relevant for intuitive HRI)	• Test protocols, objective scientific and engineering data, reference databases, and other technical inputs into standards for safe HRI (power/force-limiting, speed/separation monitoring, hand-guided operation, safety-rated monitored stop)
Sensing and perception for unstructured (or less-structured) environments Improved perception (and the ability to plan and re-plan the robot's actions based on what it "sees" and "knows") gives a robot greater autonomy, lessening its demand that its work environment meet stringent tolerances	• Sensor registration and calibration • Performance characterization (benchmarks, testbeds, and technical inputs to standards to characterize the performance of systems, subsystems, and components) • Sensing/perception engines/architectures • Proof-of-concept robotics applications of knowledge representation and reasoning
Intuitive interfaces Enabling rapid programming and training without specialized skills	• Protocols to simplify the programming, training, and rapid re-tasking of robots • Standard programming language for industrial robotics analogous to SQL or HTML
Interoperability and modularity Plug-and-play for system components, enabled by standards for physical and electronic interfaces and software interfaces or translators	• Objective technical inputs into the standard-setting process: scientific and engineering data, benchmarks, testbeds, objective third-party testing of candidate technologies and configurations
Modeling and simulation Virtual factory floor allowing modeling and simulation, calibrated based on real-time data feed from robots, machine tools, sensors, and control systems on the floor	• Robust, open, real-time operating system on the factory floor • Reference models, modeling frameworks to fully integrate robots into models of the manufacturing environment and enable robust simulation/prediction
Objective, low-cost performance characterization Making it easier for robotics users to know what they are buying and for developers and suppliers to show what their systems do	• Common performance metrics, objective data, testbeds, test methods, and benchmarks to characterize the performance attributes of advanced systems, subsystems, and components

Note: The term *infratechnology* was used in the interview process and is fully defined in Section 1.1.

1.6 WHAT DISTINGUISHES THIS REPORT

A multitude of studies investigate the potential impacts of advanced robotics. For example, a recent study by the Boston Consulting Group (Sirkin et al., 2015) stated that global labor costs could be reduced by 16% by 2025 because of advanced robotics and that labor productivity in terms of output per worker would rise by 30%. Another estimate pegs productivity gains at 25% when manufacturers adopt automation, robotics, and vision systems (Crawford, 2014). Other benefits include greater flexibility and improved quality.

Both of these studies and the insight from those we interviewed demonstrate that robotics and automation technology can yield significant cost savings, but there is less understanding of what is inhibiting the development and adoption of robotics technology. If barriers to adoption do exist, the question is *What role can government play in mitigating these barriers and accelerating the penetration of robotics technology in the U.S. manufacturing sector?* By addressing this question, this study represents a departure from most existing studies of robotics because it specifically focuses on needed technology infrastructure, which, because of its public good characteristics, is in the purview of NIST.

This report provides relevant quantitative and qualitative information for NIST to consider when prioritizing investments and research activities to support U.S. manufacturing. We also approximate national economic impacts associated with enhanced technology infrastructure. Although the confidence bands around such estimates are wide because of the many inherent uncertainties associated with prospective interview-based studies, these estimates nevertheless provide a general sense of the magnitude of potential benefits.

The remainder of this report is organized into the following sections:

- **Section 2**: Analysis Methods and Primary Data Collection
- **Section 3**: Industry Trends and Technology Gaps
- **Section 4**: Quantitative Results and Economic Impact Analysis

- **Sections 5–10**: Discussions of the six needed capabilities, including potential impacts of meeting needs, sources of market failure, and roles for NIST
- **Section 11**: Conclusion

2 Analysis Methods and Data Collection

This section presents our analytical approach to collecting and analyzing industry data and interview responses. These data were analyzed quantitatively using economic models that estimate the economic impact that enhanced technology infrastructure would have on the U.S. manufacturing sector.

2.1 DATA COLLECTION

Our data collection process began with selecting relevant sectors, identifying contacts within those sectors with the appropriate level of expertise, conducting detailed interviews with those contacts, and identifying a detailed North American Industry Classification System (NAICS) code associated with each interviewee's industry.

2.1.1 Selection of Relevant Sectors

We selected relevant sectors for end users based on the manufacturing sectors where robotics technology is used or is expected to be used more broadly as the result of improved capabilities and enhanced infratechnology. The selection of sectors is relevant for end users only.

2.1.2 Interviews

Interviews were preferable to other alternatives such as online surveys because of the complex, nuanced topics being studied. We believe that the quality and richness of information needed in this study were obtainable only through interviews during which we could provide prompts and explanations to the interviewee as needed.

Interviews were primarily conducted over the phone and lasted for approximately 1 hour each. For phone interviews, we provided the interview guide several days before the interview to help interviewees become better acquainted with the scope of our study. These interview guides are in Appendixes A and B.[17] Some interviews were conducted in person at industry events and conferences.

We identified potential interview respondents by first identifying specific developers and end users. We then searched for key personnel within those firms. To supplement this contact list, we also identified individuals through professional associations, industry association membership, and conference and meeting attendee lists, among other sources.

Respondents represented a broad set of industries that develop and use robotics and automation technologies. Respondents varied in seniority from skilled engineers to middle management to executives. Some examples of the job titles for interviewees were:

- Senior engineering manager
- Director, advanced manufacturing technology
- Senior automation engineer
- Process automation engineer/process modeling and optimization engineer
- CEO/president
- Founder
- Chief technology officer/chief technical advisor
- Global lead for manufacturing

2.1.3 Developers versus End Users

Interview questions were different for developers and for end users. Technology developers were asked to provide quantitative responses regarding the impact of

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[17] Two separate guides were used to differentiate between positions in the value chain—whether a firm develops and sells robotics technology or whether a firm uses robotics technology. Some firms are hybrid developer-users, and in these cases, we focused on the end user perspective but asked about both. We also spoke with systems integrators. Because integrators assist end users in setting up new robotic workcells, we interviewed integrators from the end user perspective. Interview questions asked about expectations for economic impact of applicable robotics and automation manufacturing technologies in terms of the percentage changes in their firm’s capital and labor, energy, and materials costs, as well as ancillary measures such as the cost of integrating robotics technology.

infratechnologies on industry sales. They were also asked to provide qualitative information on the specific infratechnologies that NIST can potentially provide. Sales impact estimates are used below to quantify the influence of public investments in infratechnologies on the size of the overall market and the extent to which end users will adopt the technologies.

End users provided quantitative responses about how robots and other automation would change the costs of four factors of production—capital, labor, energy, and materials (KLEM). They also were asked to provide qualitative feedback on barriers to adoption, key technical pain points, and how robotics and automation technologies could improve their products. Specific NAICS codes were identified for each end user interviewed so that we could separate responses by industry.[18]

The following sections outline how the quantitative responses were used.

2.2 ECONOMIC MODELS

Using the quantitative estimates provided by developers and end users associated with having the capabilities enabled by infratechnologies listed in Table 1-2 met, we estimated the impact for the United States using industry data and assumptions about applicability.

Specifically, respondents were asked to provide a percentage impact estimate for each quantitative response, with ranges being acceptable. In cases where a respondent provided a range, we used the midpoint of the range. In cases where a

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[18] The industries represented by the respondents were identified by querying a variety of sources, including the following:

- Hoover's: If the firm was listed in the database, the firm's activities were well contained within a NAICS code, and the classification matched our knowledge of the firm.
- Census NAICS Web site search with information provided by
  - the respondents about the division within their firm that they represent, or
  - descriptions of activities from company Web sites and/or annual reports.

Some respondents provided a NAICS code for their line of business. These responses were verified with a secondary search of the sources above. NAICS codes were typically identified at the narrowest level possible (i.e., five- and six-digit). Responses were then aggregated at the three- and four-digit level using applicability factors provided by respondents.

respondent provided a single point estimate, that estimate was used as if it were the midpoint.

2.2.1 Developers

Developers came from a variety of backgrounds, including industrial robot suppliers, collaborative robot suppliers, manufacturers of robot component technologies and vision systems, and robotic software developers.

National Impacts

For developers, we considered several methods to approximate the national impact of the provision of the infratechnologies noted in Table 1-3 (and in the interview guide) on the robotics market.

Developers provided estimates of the increase in their firm's sales that would result from the provision of identified infratechnologies. In some instances, developers offered an opinion not only about the impact on their firm, but also on the industry as a whole. We use this information to infer the extent to which the developers' responses apply to the industry. When we use the term "industry applicability" below, this is what it refers to.

Weighting each response by industry applicability, we applied the average responses to the RIA's 2014 estimate of U.S. shipments of $1.5 billion dollars (see Figure 3-1 for the trajectory of the market over the last 10 years). We adjusted the $1.5 billion figure upward by a factor of 3 to include the additional costs of ancillary products and services such as integration ($4.5 billion).[19]

2.2.2 End Users

Respondents were asked a question with reference to Table 1-3. Specifically, each respondent was asked to consider a hypothetical scenario: to consider the implications for KLEM if NIST was immediately able to meet each of the defined capabilities in the table through the provision of identified infratechnologies.

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[19] The other methods that we considered were based on data from end users. We considered using the net change in capital costs as a lower bound for the potential increase in the sales of robotics or the total estimated benefits/value to end users as an upper bound for the potential increase in sales of robotics.

It is important to note that not all respondents were willing or able to provide quantitative estimates of impacts on costs. For example, one end user stated that enhanced robotics and automation technology would improve the yield in semiconductor and electronics manufacturing; however, this end user was unable to provide a percentage impact for materials costs. These kinds of responses could not be included in the final quantitative assessment. For respondents who provided an estimate for at least one KLEM category, we conservatively assigned zero impact to the categories for which they did not respond.

National Impacts

The percentage impact estimates were assumed to apply to each respondent’s four-digit NAICS code. Table 2-1 summarizes the four-digit NAICS codes in our interview sample.

Respondents provided impacts for higher and lower levels of industrial classification, but the four-digit level was the minimum level at which estimates were summarized. We assume that responses at the five- and six-digit levels apply to the four-digit level. Respondents providing impacts for higher levels of aggregation (e.g., three-digit level) had their responses applied to all four-digit NAICS codes within the three-digit NAICS level that were not already represented by other respondents.

Table 2-1. End User Industry Coverage

- Food manufacturing
- Wood product manufacturing
- Plastic products manufacturing
- Alumina and aluminum production and processing
- Machine shops; turned product; and screw, nut, and bolt manufacturing
- Other fabricated metal product manufacturing
- Computer and peripheral equipment manufacturing
- Semiconductor and other electronic component manufacturing
- Household appliance manufacturing
- Motor vehicle manufacturing
- Motor vehicle body and trailer manufacturing
- Motor vehicle part manufacturing
- Aerospace product and part manufacturing

The number of responses varied by four-digit manufacturing NAICS code. Overall, we received quantitative responses for four-digit industries that represent 36.5% of the sales of the manufacturing sector.[20] We believe that other manufacturing industries for which we lack responses would benefit from the provision of the identified infratechnologies. This under-representation makes our estimates conservative.

Respondents were also asked to provide industry applicability factors for their impact estimates. For the vast majority of respondents, these factors were 100% (i.e., respondents expected their impact estimates to hold for all firms in the industry). Responses less than 100% were often stated as a fraction of the industry or for a particular type of firm or set of firms within the industry. When a specific fraction of the industry was not provided, we relied on secondary estimates such as market shares from sources such as IBISWorld reports.

First, we looked for outlying impact estimates that were judged to be unrealistic or heavily biased upward.[21] After looking for outliers, we considered several possible ways to summarize the responses within each NAICS code, including the following:

- Average: a simple average of the midpoint impact response for all respondents
- Sales-weighted: a weighted average of midpoint impact responses based on the size of the respondent's firm

We decided to use the simple average method because it was less susceptible to outlier influence.

To estimate cost-to-sales ratios for each KLEM factor input, we used industry data from national accounts provided by the Bureau of Labor Statistics (BLS) for energy and materials cost estimates.[22] The data provided by BLS gave highly aggregated accounts for capital and labor. To better identify capital and

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[20] Sales for the manufacturing sector are defined as all sales within NAICS 31–33.

[21] We did not exclude any responses for end users.

[22] Energy costs included the manufacturing industry's purchases of oil and gas extraction (NAICS 211), coal (NAICS 2121), electricity (NAICS 2211), natural gas (NAICS 2212), and refined petroleum (NAICS 324). Materials costs included purchases from other manufacturing industries in the NAICS range 3210–3330, excluding 324 (refined petroleum and coal).

labor costs associated with shop floor activities, we relied on the 2013 Annual Survey of Manufactures.[23]

Using industry data on cost-to-sales ratios, we estimated the KLEM national factor expenditures for each industry in Table 2-1. We then reduced the national factor expenditures for each industry by the average industry applicability factor, which yielded a national factor expenditure for each industry. Then we applied the average percentage impact on costs to the national factor expenditure for each industry. This adjustment yielded industry-level cost impacts for each industry for each of the four factor inputs. The total cost impact across industries is the sum of the industry-level impacts.

We apportioned the total cost impact to each of the six capabilities in Table 1-3 by using the average share of importance points awarded to each capability. We used only the importance scores provided by end users (see Section 3.3 and Appendix C on importance scores).

For example, if an interviewee awarded a total of 20 points across the six capabilities, and he or she provided the highest importance score of 5 to safe HRI and 2 for objective, low-cost performance characterization, then the shares would be 25% and 10%, respectively. We then averaged these shares across individuals and applied them to the total cost impact.

2.3 CONSERVATIVE NATURE OF THE ECONOMIC MODELING APPROACH

The quantitative economic impact estimates calculated in this study are considered to be conservative in that they do not capture all the benefits that would result from an improved technology infrastructure. As will be discussed below, our analysis focuses on reductions in manufacturers’ production cost that would result from meeting the identified technology infrastructure needs. However, this does not capture all of the potential economic benefits associated with an enhanced technology infrastructure.

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[23] Capital costs include capital expenditures on machinery and equipment, computer and peripheral equipment, and other machinery and equipment. Labor costs include production workers’ annual wages grossed up to include nonwage benefits such as health insurance, retirement, and other fringe benefits.

For example, a streamlined infrastructure for creating, transmitting, analyzing, and communicating design and production data would accelerate the development and commercialization of altogether new product markets. These new products would have increased economic value stemming from enhanced attributes, such as greater functionality, lower maintenance costs, and increased life expectancy.

However, valuing new (yet to be defined) products or product attributes is difficult, has great uncertainty, and is beyond the scope of this study.

An improved technology infrastructure will also lead to reduced R&D costs. However, interviewees were not able to quantify R&D savings, saying that the benefits would be a mixture of improved/accelerated R&D and enhanced product quality. Hence, these categories of benefits are discussed qualitatively but are not included in the quantitative economic impact estimates.

In general, focusing on manufacturing cost savings implies that the analysis captures primarily gains in producer surplus and does not capture gains in consumer surplus associated with improved product quality. In addition, the analysis does not capture increases in social welfare from increased output (sales), which result from lower cost and higher demand. The analysis also does not capture increased exports that would result from the enhanced competitive position of U.S. manufacturers.

For these reasons, the economic impacts presented are considered to be conservative, lower-bound estimates. These estimates should also be interpreted as benefits per year. Benefits were quantified for a single year using recent industry data at NIST’s request; enhanced technology infrastructure would last significantly longer than just 1 year.

3 Industry Trends and Technology Gaps

More robots are used in factories today than at any other time in history, and global and U.S. outlooks show that purchases of robots are expected to increase in the near term.

The use of robots has largely been limited to factories in the United States and other industrialized nations such as Japan and Germany, but shipment data show that China is now one of the largest buyers of robots in the world and some developing nations like Mexico have increased purchases of robots. The vast majority of the global stock of robots falls into the class of traditional industrial robots.[24] Traditional industrial robots have also been highly concentrated in automotive manufacturing rather than having a broad-based pattern of adoption across manufacturing industries.

A new generation of cutting-edge collaborative robots is starting to reshape the market for manufacturing robots by expanding the applications that robots can be tasked with and by removing some of the barriers that have prevented broader adoption. Collaborative robots—which are a relatively novel product offering in the market—provide a new option along the price-performance gradient that may allow more SMEs to begin to experiment with robotics with less risk. This trend is reinforced by the long-term trend of an improving performance-to-price ratio for industrial robotics that has been in motion since the early 1990s.

Although current trends signal increased adoption of robotics in the near term, sources of market failure still impede the

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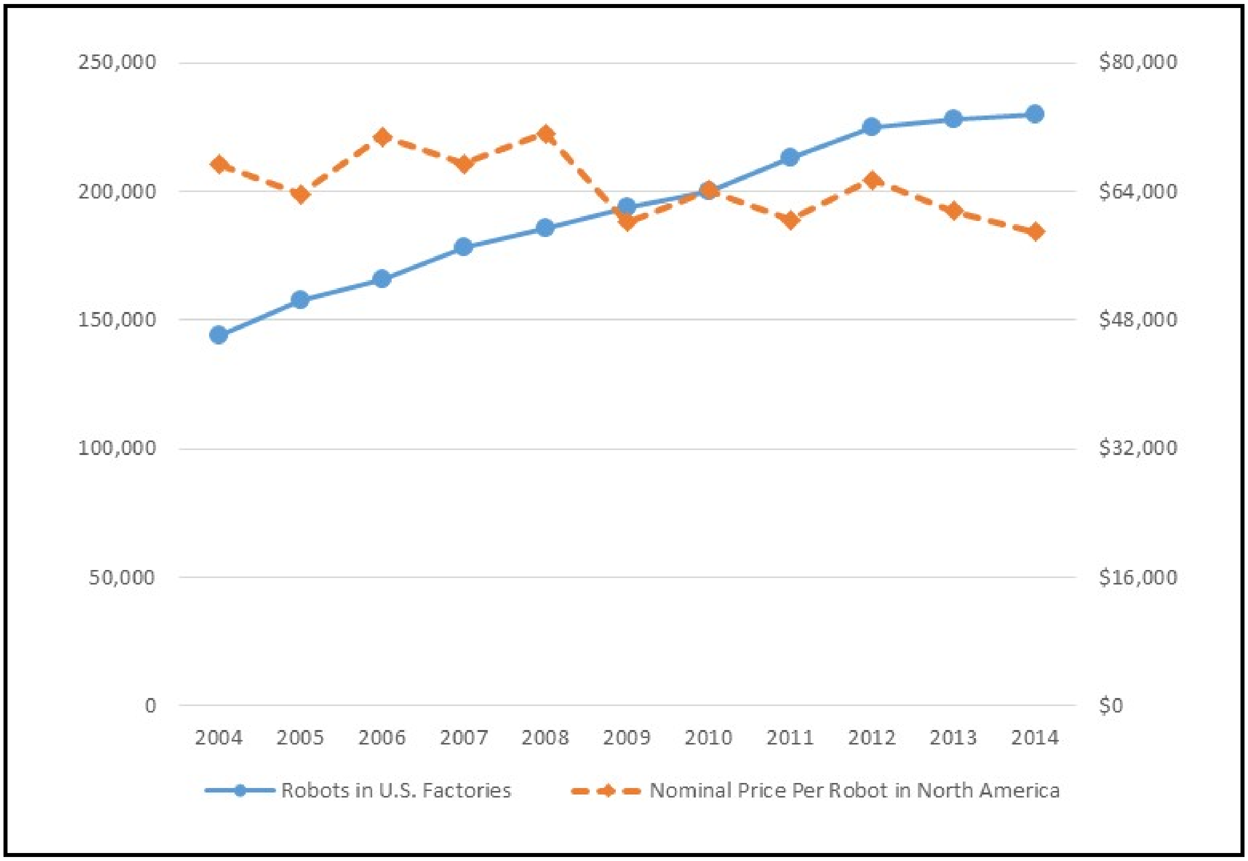
[24] We have previously defined traditional industrial robots to mean the large, powerful, fast-moving robots that operate in safe, guarded space, cordoned off from factory workers.

efficient development and adoption of robotics technology. To understand the barriers that bring about this market failure, and the initiatives that NIST might pursue to alleviate them, RTI gathered perspectives from stakeholders positioned along the robotics and automation value chain.

3.1 TRENDS IN ROBOTICS AND AUTOMATION

By the end of 2014, about 1.5 million industrial robots were in operation around the world (International Federation of Robotics [IFR], 2015). Japan has the largest installed base of robots of any country in the world, with the United States ranking second. The RIA estimates that the stock of industrial robots in use in U.S. factories is 230,000 as of 2014, which represents a 60% increase since 2004 (see Figure 3-1).

Figure 3-1. U.S. Stock of Robots and the Nominal Price per Robot, 2004–2014



Source: Robotic Industries Association (2004–2014).

The cost of robots has been falling, thus making robots more accessible to SMEs. Furthermore, a new generation of "collaborative" robots is being offered at a lower point along the price-performance gradient. The availability of this new generation of robots helps to lower the barrier to entry for manufacturers that have not yet adopted robotics technology.

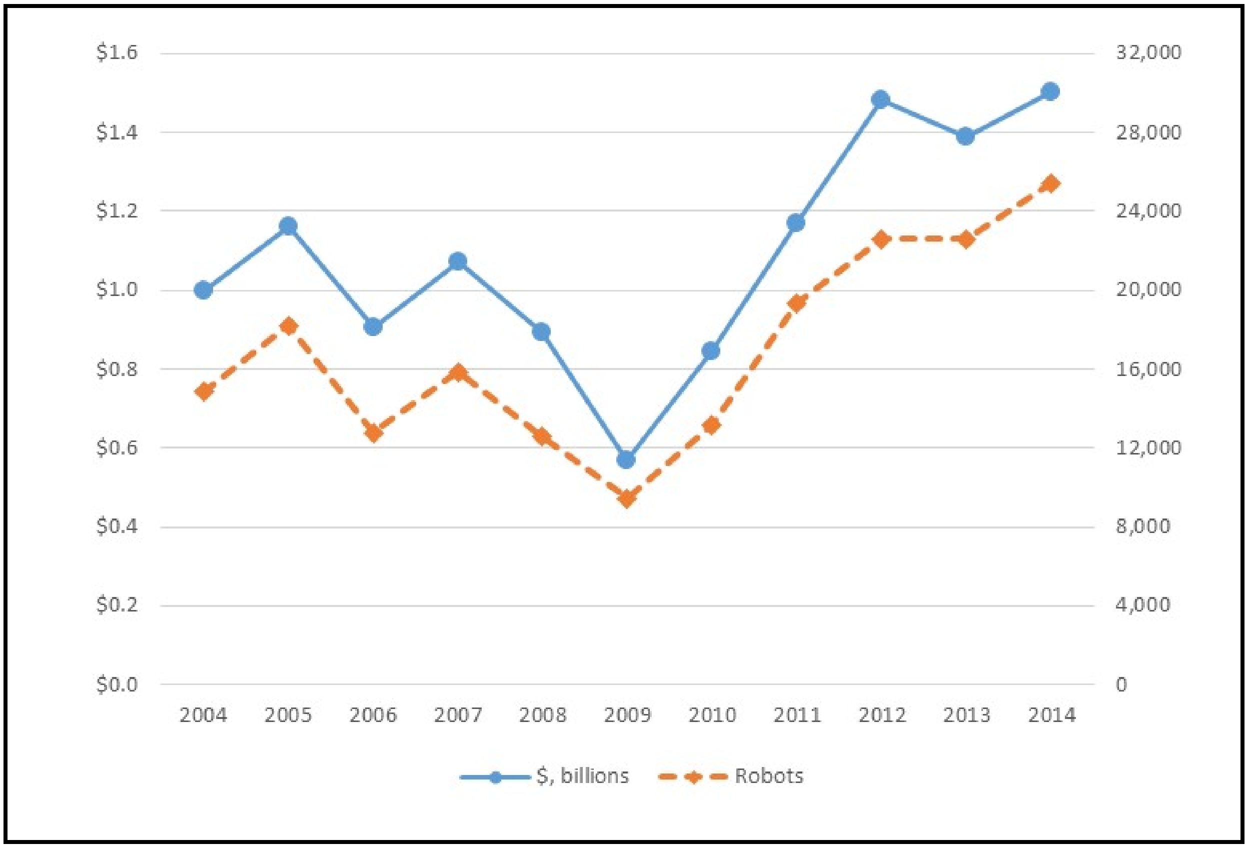
Sales of robots in the United States appear to be cyclical and depend on the investment cycles of U.S. industries, in particular the automotive industry. However, many experts expect non-automotive industries to begin increasing their demand for robots. Figure 3-2 shows that the industry contracted during the Great Recession (which lasted from December 2007 to June 2009 [National Bureau of Economic Research, Public Information Office, n.d.]) and reached a 10-year low during 2009. The robotics industry has since recovered, and in 2014, 25,425 robots were sold to companies in North America, yielding $1.5 billion in revenues for robotics suppliers in North America. The volume of robots sold and the revenue generated are record highs for the industry. The volume of new orders suggests that the industry will continue to expand at least in the near term.

Global Outlook

IFR (2015) expects that there will be a 15% compound annual growth rate (CAGR) in global robot installations from 2016 to 2018. Robot purchases are expected to be strongest in Asia/Australia, followed by the Americas and Europe (see Table 3-1).

The main customer of industrial robotics globally is the automotive sector. Given its purchasing power, the automotive sector is arguably the single largest customer for robotics technology. The electrical/electronics industry is also substantially increasing its global investments in robotics (IFR, 2015). Other industries that have recently been increasing orders globally include rubber and plastics manufacturing, pharmaceutical manufacturing, food and beverage manufacturing, and metal and machinery manufacturing.

Figure 3-2. Shipments of Robots to North American Customers, 2004–2014



Source: Robotic Industries Association (2004–2014).

Table 3-1. Forecast CAGR in Industrial Robot Installations, 2016–2018

Geography	Forecast CAGR, 2016–2018
Asia/Australia	18%
Americas	10%
Europe	10%
Global	15%

Source: International Federation of Robotics (2015).

A recent analysis by the Boston Consulting Group considered two factors that will influence how quickly different industries adopt robots in the future. The first factor is the cost-effectiveness of substituting robots for human labor. The second factor is the degree to which production tasks are automatable—which was defined as occupational tasks that could potentially be replaced by available technology. This emphasis yielded four industries that are most likely to lead adoption globally: computers and electronic products; electrical equipment, appliances, and components; transportation equipment; and machinery (Sirkin et al., 2015).[25]

U.S. Outlook

The U.S. outlook largely mirrors the global outlook. The automotive industry has been the primary driver of growth in the use of robots in the United States and in most industrialized nations. Non-automotive industries that increased orders in 2014 by the largest percentages were plastics and rubber, semiconductors and electronics, and metals. The fastest growing applications for robot orders in North America (United States–specific data not available) in 2014 were welding (arc and spot), assembly, and material handling.

Venture capital investments in robotics technology, a potential indicator of future growth of the U.S. robotics market, nearly tripled from 2011 to 2013 according to a report by PricewaterhouseCoopers (2014).[26]

3.1.1 Robot Performance-to-Price Ratio

Notwithstanding the differences between traditional industrial robots and the new generation of advanced collaborative robots, prices of robots have fallen substantially since 1990. For example, without adjusting for quality, prices for robots used in electronics manufacturing decreased by roughly 45% between 1990 and 2005. With quality adjustments, prices decreased by nearly 80% during this time frame (Mathia, 2010). Based on these trends, Kent Massey of HDT Global equates this to a doubling of the performance-to-price ratio every 4 to 10 years depending on the particular assumptions that are made (personal communication, June 13, 2014).

Integration costs are also starting to fall. Based on our conversations with industry experts, the total cost of robotic systems (initial costs plus integration costs) tends to be 3 to 4

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[25] It is important to note that enhanced technology infrastructure, which is the focus of this study, may influence industries' propensity to adopt robots in ways different from those outlined in the Boston Consulting Group report (Sirkin et al., 2015). Nevertheless, this is a useful framework for thinking about the likelihood of adoption moving forward.

[26] The influx of venture capital investment in the robotics market will likely spur innovation for robotics for the manufacturing environment and for robotics in the consumer products, agriculture, logistics, public safety, health care, and service industries.

times the initial costs of each robot; however, that ratio is changing. Integration costs include ancillary products and services required to get the robot up and running. IFR (2013) estimates a 3X multiplier for ancillary products and services, which is in line with the opinions of industry experts.

This high fixed cost has been a barrier to adoption for SMEs. An interviewee expressed his opinion about adoption costs of a robot in the following way: "Traditional robotics has always required an integrator, but now with collaborative robots you don't need a system integrator and that's what really reduces the cost of the robot."

The trend toward lower integration costs benefits all manufacturers, especially SMEs. Furthermore, with the growth of collaborative robotics, a broader range of offerings is starting to emerge along the price-performance gradient. Low-cost, lower-payload robots that somewhat break the mold of traditional industrial robots are typically offered at lower price points. Additionally, some robotics companies have made efforts to simplify the integration process as part of this collaborative trend.

Notwithstanding, technology infrastructure needs remain, and if provided, would further lower the total cost of adoption.

3.1.2 Traditional Industrial Robotics versus Collaborative Robotics

Advanced robotics is distinguished from traditional industrial robots by capabilities such as adaptable and reconfigurable assembly, autonomous navigation, dexterity (a balance of precision and compliance in robotic hands, or end effectors), perception suitable for semi-structured and unstructured environments, and the capability to work safely in close proximity to people.[27] As articulated by the Advanced

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[27] These capabilities are highlighted in *A Roadmap for U.S. Robotics—From Internet to Robotics* (Robotics-VO, 2013), which also discusses model-based integration and design of a supply chain, nano-manufacturing, and green manufacturing. Some elements of these capabilities are also discussed here. For example, supply chain modeling and integration connect this section of the report with its companion report (*Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing: Smart Manufacturing Processes*). As another example, improving the energy efficiency of robotic systems (consistent with green

Manufacturing Partnership, which falls under the Advanced Manufacturing Initiative and the proposal for a National Network for Manufacturing Innovation, advancements in enhanced robotics capabilities could potentially increase the competitive position of the U.S. manufacturing sector in global markets, specifically through reducing manufacturing costs and enhancing the quality and customization of manufactured goods.

Traditional industrial robotics represents a relatively mature set of technologies. Developers of industrial robots have learned over time the best ways to build these systems. System integrators and end users in manufacturing have similarly learned over time how to deploy them. Advanced robotics, by contrast, is an emerging technology area characterized by a high degree of technical and market risk, including the best ways to build new functionality into robotic systems and the best ways to deploy robots with greater functionality, particularly where HRI or collaborative robotics is involved.

Traditional industrial robotics are well suited where there are large production runs (for which the high cost of commissioning the robotic systems for a single run can be amortized over hundreds of thousands or even millions of units) and where automated processes can be isolated spatially, or caged off, from areas where people need to be working. The potential for advanced robotics to add value to the manufacturing sector is great, especially for small production runs with frequent line changes (agile manufacturing) and for situations where it would be economically advantageous for robots and people to work side by side (collaborative robotics).[28]

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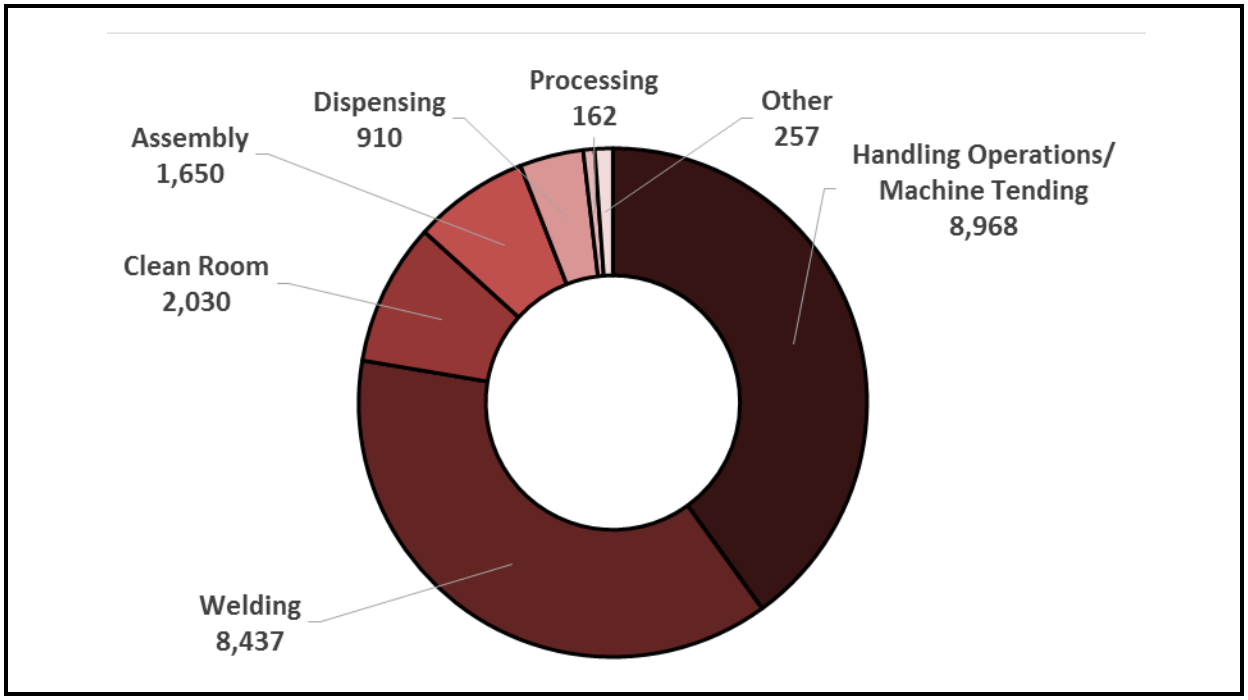
manufacturing principles) and improving the safety of robots working in close proximity to people are linked because light weighting of robotic arms is critical to both capabilities.

[28] The availability of more flexible and versatile robotic systems may be especially advantageous for SMEs. In the United States, manufacturing establishments with fewer than 250 employees represent 57% of manufacturing employment and 46% of wages (Bureau of Labor Statistics, Quarterly Census of Employment and Wages, based on 2013 first-quarter manufacturing employment). The higher average wages for production workers in larger establishments are consistent with higher labor productivity resulting from the typically higher degree of automation. This suggests at least a *prima facie* case that wages should be expected to rise at smaller establishments as advanced robotics technology makes its way into the market.

The distribution of the current generation of robots (primarily, traditional industrial robots) by manufacturing applications (Figure 3-3) and by industry (Figure 3-4) provides insight into the current use of traditional industrial robots and potential opportunities for the next generation of advanced robots. For example, traditional industrial robots are used extensively in the automotive industry, particularly in body and paint shops. Final assembly, however, which accounts for roughly one-half of an automaker's production schedule, is still performed almost entirely by hand. Automating final assembly tasks would involve a high degree of HRI. Collaborative robotics technology and associated technology infrastructure has not yet advanced to point where these tasks could be automated.

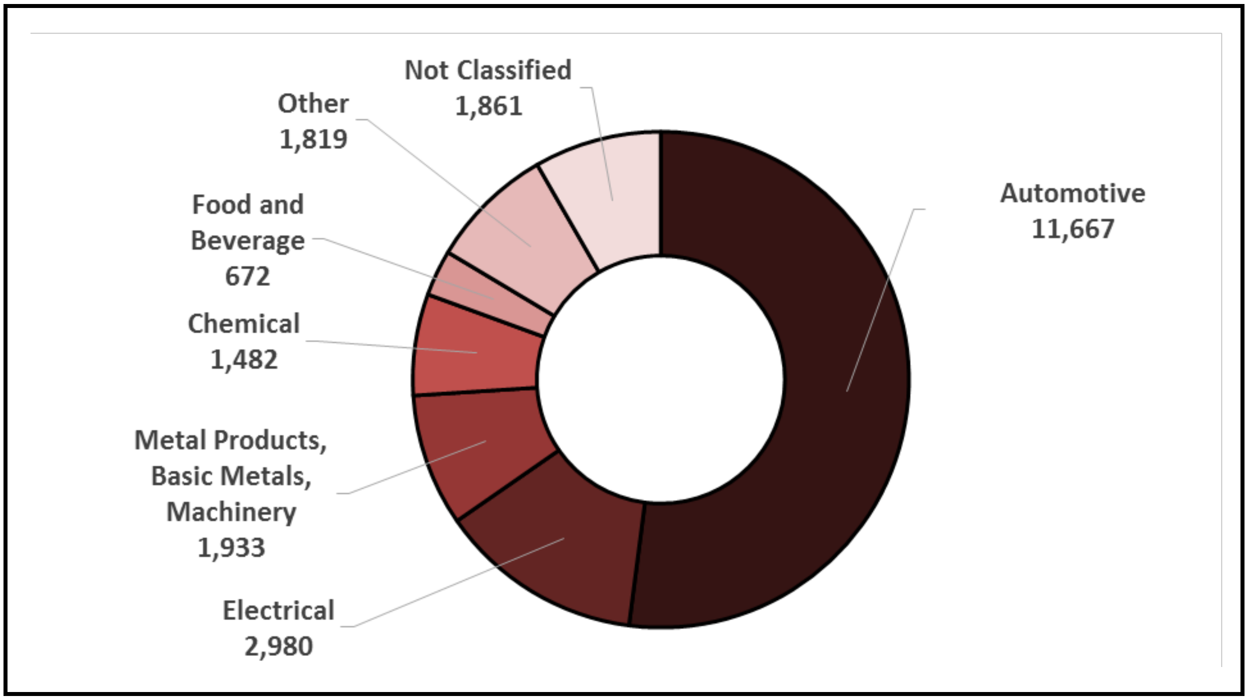
A similar practical difficulty inhibits the automation of aircraft assembly. Workers are frequently present in and around the area in which the aircraft is being built, thus making the use of traditional industrial robots somewhat unsafe. The same is true for electronics manufacturing.

Figure 3-3. Distribution of Robots in the United States, by Major Application Area (Based on 2012 U.S. Shipments)



Source: International Federation of Robotics (2013, p. 70).

Figure 3-4. Distribution of Robots, by Industry (Based on 2012 U.S. Shipments)



Source: International Federation of Robotics (2013, p. 70).

The emerging trend toward using advanced robots for agile manufacturing and collaborative interaction is reflected in the greater number of less expensive, lower-payload robots sold in the United States over the last decade. From the perspective of one industry observer, a decade ago, a much larger fraction of traditional industrial robots sold in the United States had payloads in the range of 50 to 200 kilograms and cost between $150,000 and $250,000; whereas today, there are more lower-cost robots with payloads of 5 to 50 kilograms.[29] Furthermore, when accounting for the cost of integrating a traditional industrial robot into a workcell, the total cost of the system can typically be many times the initial cost of the robot, making the technology cost-prohibitive for SMEs that do not have sufficient production volumes across which fixed costs can be amortized. Many industry observers and participants believe that a potential advantage of collaborative robots is that they would be easier to integrate with existing production lines because their size and payload mimic those of humans and the software

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[29] The average price of industrial robots sold in the United States has fallen from around $80,000 in 2000 and 2001 to between $60,000 and $65,000 from 2009 through 2012 (adjusted for inflation) (IFR, 2013, p. 55).

interfaces tend to be more user-friendly. More specifically, an interviewee noted, “One anticipated consequence of this new generation of collaborative robots is that they can be deployed in unstructured environments. [Manufacturers] don’t have to bolt the equipment to the floor, cages, etc. That whole model will still exist, but the collaborative model will allow the user to take on the integrator role, and allow the robot to be deployed in different locations based on need.”

Some collaborative robots are claimed to be inherently safe because they are physically lighter and manage a smaller payload, but this is not necessarily the only way to achieve safe human-robot collaboration. One end user described participating in a demonstration with a robot capable of supporting a 250-kilogram payload while being manipulated by hand. One software developer who works closely with end users of manufacturing robots described participating in demonstrations in which an “intelligently safe” robot adjusted its speed or motion paths (in extreme cases, stopping altogether) to accommodate people moving in and out of its workspace. At a collaborative robotics conference, one company demonstrated a collision avoidance technology where a robot arm not only slowed down and stopped when it sensed a human arm in its range of motion, but it also moved out of the way when the human arm tried to initiate contact.

Another key aspect of collaborative robots is the ease of programming and setup. Some collaborative robots such as Rethink Robotics’ Baxter and Universal Robots’ UR3[30] have more friendly interfaces for setup, although this is not an industry standard.

Another area of growing interest in collaborative robotics is combining robot arms and end effectors with mobile robot platforms, but many technical hurdles remain to be solved before these systems are widely available. Several industry experts expressed the view that the technology for safe HRI in applications like these and others is developing rapidly but that

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[30] Rethink Robotics, based in Boston, Massachusetts, sells the Baxter and Sawyer robots. Universal Robots, based in Denmark, sells the UR10, UR5, and UR3 robots.

safety standards would need to catch up with the technology before it can be fully used.[31]

3.2 INDUSTRY CAPABILITIES AND POTENTIAL BENEFITS

Table 3-2 reproduces the information in Table 1-3 for convenience, with an additional column for the potential benefits associated with each capability being realized.

Table 3-2. Required Capabilities for the Application of Advanced Robotics in Manufacturing, Associated Infratechnology Needs, and Benefits

Industry Capabilities	Examples of Infratechnology to Help Meet Needs	Potential Benefits and Impacts
Safe human-robot interaction (HRI) Universal standards for developers of robotics technologies and the application of these technologies in manufacturing settings with robots working in close proximity to people (see more below on sensing/perception for unstructured environments, relevant for intuitive HRI)	• Test protocols, objective scientific and engineering data, reference databases, and other technical inputs into standards for safe HRI (power/force-limiting, speed/separation monitoring, hand-guided operation, safety-rated monitored stop)	• More flexible, smaller-footprint production lines • New and creative use cases of robots working in close proximity and in collaboration with people • Lower integration costs • Improved safety • Reduced market risk for developers • Reduced liability for end users • Increased adoption of collaborative robots
Sensing and perception for unstructured (or less-structured) environments Improved perception (and the ability to plan and re-plan the robot's actions based on what it "sees" and "knows") gives a robot greater autonomy, lessening its demand that its work environment meet stringent tolerances	• Sensor registration and calibration • Performance characterization (benchmarks, testbeds, and technical inputs to standards to characterize the performance of systems, subsystems, and components) • Sensing/perception engines/architectures • Proof-of-concept robotics applications of knowledge representation and reasoning	• Lower integration costs associated with accommodating tolerances • Flexible navigation of unstructured or less-structured environments • More flexible plant layouts • Improved safety • Optimized robot motions • Data streams to calibrate simulation models

(continued)

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[31] Some simple implementations of human-safe robots are already in use. In automotive assembly, for example, automated guided vehicles (AGVs) deliver parts from one area of the factory to another. Sensors cause the AGVs to stop when a person steps into their path or when they encounter unexpected contact. See, for example, this video: http://www.youtube.com/watch?v=cCR0Bmw5TxI.

Table 3-2. Required Capabilities for the Application of Advanced Robotics in Manufacturing, Associated Infratechnology Needs, and Benefits (continued)

Industry Capabilities	Examples of Infratechnology to Help Meet Needs	Potential Benefits and Impacts
Objective, low-cost performance characterization Making it easier for robotics users to know what they are buying and for developers and suppliers to show what their systems do	• Common performance metrics, objective data, testbeds, test methods, and benchmarks to characterize the performance attributes of advanced systems, subsystems, and components	• Reduced uncertainty • Improved understanding of new technologies • Increased adoption of robotics by SMEs
Interoperability and modularity Plug-and-play for system components, enabled by standards for physical and electronic interfaces and software interfaces or translators	• Objective technical inputs into the standard-setting process: scientific and engineering data, benchmarks, testbeds, objective third-party testing of candidate technologies and configurations	• Plug-and-play functionality • Reduced integration costs (physical and software interfaces) • Modular development of systems • Increased adaptability of robotic systems • Scalable, reconfigurable, and reusable robotic systems • Reduced retooling costs • Increased adoption in industries with small production runs
Intuitive interfaces Enabling rapid programming and training without specialized skills	• Protocols to simplify the programming, training, and rapid re-tasking of robots • Standard programming language for industrial robotics analogous to SQL or HTML	• Simplified programming • Reduced setup time and setup costs • Enables individuals without specialized training to commission a robotic system
Modeling and simulation Virtual factory floor allowing modeling and simulation, calibrated based on real-time data feed from robots, machine tools, sensors, and control systems on the floor	• Robust, open, real-time operating system on the factory floor • Reference models, modeling frameworks to fully integrate robots into models of the manufacturing environment and enable robust simulation/prediction	• Control of processes from central dashboard • Improved prediction • Adjustments can be optimized • Reduced delay and work stoppage • Software reconfigurable factory floor • Reduced retooling costs • Improved “as-built” documentation • Using robot teaching to refine simulation models

The following subsections describe each of the six capabilities individually, the associated infratechnology that would help meet the needs of industry, and potential benefits of these capabilities being realized.

3.2.1 Safe Human-Robot Interaction

With traditional industrial robots, the risk assessment process and the onus of responsibility are well understood. The same cannot be said of safe HRI in the paradigm of advanced robots, especially collaborative ones. Infratechnologies such as standards and methods to characterize safety are needed to address three fundamentally different approaches to, or models of, safe HRI: First is the power-limiting or force-limiting robot, typically smaller and lighter with a lower payload, which is unable to exert enough force to cause serious injury to a person; second is speed and separation monitoring to enable a robot of any size to perceive (using onboard sensors, area monitors or sensors, or some combination) a person entering its work area and accommodate that person by slowing down, entering a “soft-servo” state, or stopping completely; and third is hand-guided operation, or applications in which a robot augments the force applied by the operator—the operator provides the perception, dexterity, and judgment. The potential impacts of these approaches to safe HRI include the removal of cages, which, in the long term, means more flexible, smaller-footprint production lines, new and creative use cases of robots working in close proximity and in collaboration with people, lower integration costs, and improved safety.

Comments from industry are consistent about the need for multiple approaches to safe HRI. One developer suggested that “lighter is inherently safer,” using the example of a 4-pound arm that is able to lift 16 pounds being safer than a 16-pound arm that can lift 4 pounds. Others pointed out that safe HRI can be supported by other capabilities such as enhanced sensing and perception, simulation, and a better-trained workforce. For power- and force-limiting robots, research is needed to characterize materials suitable to replace cast aluminum and cast iron currently used in robotic arms. For speed and separation monitoring, research in sensing and perception is needed.

Safe HRI can make the manufacturing environment more productive by complementing the existing workforce. Dull, repetitive, and often ergonomically taxing tasks can be performed by the collaborative robot while a worker monitors the collaborative robot and focuses on higher value-added tasks. One end user stated that with the right training and development of user-friendly interfaces, collaborative robots could potentially be labor enhancing rather than labor replacing. Although large potential benefits can be reaped from safe HRI, it may also be out of reach of SMEs because there are not currently any low-cost tools for measuring safety in this new paradigm.

The first robot safety standard (not human-robot safety standard) was published in 1986 and was updated in 1992 and 1999. The 1999 standard was active until 2013. Overall, the safety regime from 1986 to 2013 has been to eliminate HRI with no consideration of any potential foregone benefits. Since about 2006, there has been acknowledgment that HRI will be the next standard, and it has gained more attention over the last few years. As one industry observer noted, interactions in the field are still very conservative in terms of how far the working envelope is being pushed. The same observer noted that many assumptions being made could be deemed conservative in nature, or they could be based on the average industrial worker who does not really exist. The ability to tailor assessments of safe HRI to the unique characteristics of a particular application is the goal that industry would like to work toward, but many challenges, including a lack of infratechnologies, may hinder progress in this direction.

The International Organization for Standardization (ISO), the American National Standards Institute (ANSI), and the RIA are the principal organizations involved in promulgating safety standards for robotics. The standard-setting process involves collaboration among developers and users of robotic systems with the involvement of NIST. Standards for safe HRI have existed since 2006, but the current standard (ANSI/RIA R15.06, the U.S. adoption of ISO 10218) devotes fewer than 10 pages out of a 150-page document to collaborative robot applications. ISO has been working on Technical Specification 15066 (TS 15066), informed by research conducted at the University of Mainz, which provides more guidance for the use of power- and force-limiting robots. This standard was originally planned for release in 2015, but it required additional development and was only recently released in February 2016.[32] According to a recent blog post summary of TS 15066 by a gripper manufacturer, the new technical specification adds three items to the existing standard:

- Data on maximum allowable robot speed associated with specific human pain levels for various body parts

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[32] http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=62996

- More in-depth explanations of the different modes of human-robot collaboration
- What to include in collaborative robot risk assessments (Bélanger-Barrette, 2016)

Standards for other models of safe HRI, such as hand-guided operation and speed and separation monitoring, are considered to be more futuristic. Having the language describing these models opens the door for future development, but widespread commercial applications are not expected in the immediate future.

The Fraunhofer Institute for Manufacturing Engineering and Automation in Germany has also worked on producing data on the collision of robots and humans in an industrial environment; this is described by the term *dynamic impacts*. In a technical paper, authors from the Fraunhofer Institute compare the need for standardized safety tests for robots to the crash testing that is standard in the automotive industry: “Whereas it is widely accepted in the automotive industry to take a standardized sample of crash tests scenarios that are evaluated on anthropomorphic test devices, so called crash test dummies, robotics science still lack uniform tests that can be carried out for different systems” (Oberer, Malosio, & Schraft, 2006). Uniform safety tests for automobiles were not required in the United States until the 1970s, more than a century after automobiles were invented and more than 4 decades after Henry Ford’s Model T was widely available. U.S. experience in automobile safety shows that a sufficient body of science had to accumulate before safety standards were established. A similar body of science might have to accumulate for robotics, but NIST could accelerate the development of fundamental metrology needed for standard robotic safety tests.

Next-generation collaborative robots will require next-generation safety standards, which will need to be informed by objectively evaluating the capabilities of collaborative robots, with standards consistently applied across companies. In short, there is a need for “critical technical inputs to standards,” as discussed in the Roadmap for U.S. Robotics (2013, p. 22). The world’s first traditional industrial robots were installed in U.S. automotive plants in the early 1960s, but collaborative robots have only recently entered the market. The newness of the technology suggests that much more basic research needs to be done to understand HRI. As the body of science grows and standards for safe HRI are formulated and adopted by the manufacturing sector, there will also be a need for low-cost risk assessment tools and simulation models that will help end users comply with safety standards and better understand and quantify the potential risks of HRI.

Companies that are now developing collaborative robots self-assert the safety of the robots based on their own metrics stating, for example, that a robotic arm is not capable of exerting a force greater than a certain threshold and is therefore inherently safe. The absence of universal force measurement standards makes it difficult for end users to compare product offerings and choose the best solution to meet their needs.

Moving toward universal standards for safety would also give developers a common target, which would reduce the market risk faced by developers (the risk that a technically successful solution would fail to find a market large enough to provide an adequate return on investment). The infrastructure needed to test and certify that robotic systems meet universal standards would also be an asset to developers aiming to meet the standards. Datasets or libraries, for example, of common human poses and motions would be helpful in developing technology to make robots better able to perceive the behavior of people around them and in testing that a new system meets a universal standard for this capability.

Understanding how common aspects of an application contribute to safety is critical. To reduce liability, manufacturers often rely on a third-party integrator to come in, set up the workcell, and do a thorough risk assessment. One developer pointed out that one of the main benefits of collaborative robots is reducing the need for integrators. Integration serves to shift risk away from the end user to the company doing the integration to some degree, but it comes at a high cost. Manufacturing companies may hire an integrator (either the robot manufacturer's integration team or a third-party integrator) because of liability concerns associated with setting up collaborative workstations on their own. One industry observer pointed out the need to apply safety standards and certifications to entire integrated systems, not only to individual robots; the point being that it is possible to integrate two inherently safe robots in a way that may not be safe at the systems level.

One end user indicated that the limited reach and payload of human-safe robots currently on the market are limiting factors to adoption. A real opportunity would be to have a robot that could support a heavy part in a “soft-servo” state that allows a person to manipulate the part and perform detailed work, then return control to the robot for further processing.

3.2.2 Sensing and Perception for Unstructured Environments

The current limitations of the ability of robots to sense and perceive individuals, obstacles, and other objects constrain the extent to which robots can be moved from structured workcells into unstructured or semi-structured factory environments. Improved perception of its environment may enable a robot to be more flexible. One end user offered the example of a wire form that the robot must bend into an exact shape. Tolerances of 1/16th of an inch were acceptable for the wire form, but the robot would enter a fault state and thus stop working if it did not find the form within 3/1,000ths of an inch of where it expected it to be. In general, accommodating such high tolerances involves costly and time-consuming effort to design a robot’s environment. Greater flexibility afforded by improved sensing and perception capabilities could lower these costs.

Improved sensing and perception depend on the technical capabilities of hardware combined with software and related algorithms. Sensing and perception includes vision systems and tactile perception systems. Sophisticated examples of vision systems include object differentiation through object recognition and object characterization (surface body characteristics, inertial characteristics), and the ability to track humans in the manufacturing environment. Two- and three-dimensional sensing technologies are relevant depending on the particular use case. Sophisticated examples of tactile perception systems include methods of force sensing and robot dexterity, which are more futuristic and have potentially large benefits.

There is a need to better characterize the performance of different types of sensors in different factory environments. Infrared sensors, for example, may not perform optimally in the presence of fiberglass, which absorbs infrared light. In general, it would be useful to characterize the visibility of different materials to different kinds of sensors. Materials that are optimized for robot visibility could be incorporated into work smocks, for example. euRobotics AISBL (2014) asserts that the most important barrier to perception ability "is the limitation of the sensor technology for accurate measurement of specific materials (reflective, absorbing, and transparent) using off the shelf, affordable and eye-safe sensors. Fusing these different modalities together into a common representation is also not generally solved. Currently, common sense knowledge is integrated only at higher level systems, but methods are missing to select which information to use at the sensor fusion level" (p. 103).

Sensing that relies on wireless communication (e.g., area sensors that track the movement of people on the factory floor) may be subject to interference. One end user described having problems with arc-welding scrambling wirelessly transmitted data and suggested that it would be useful to have objective data characterizing the robustness of wireless communication systems to the types of interference frequently encountered in factory environments. The need for robot-specific wireless communication protocols, suitable to handle latency requirements, remote haptic feedback, data security, and cloud-processing of high-level cognitive functions, is discussed in the *Robotics 2020 Multi-Annual Roadmap* (euRobotics AISBL, 2014, p. 148).

The need for cognitive architectures for the "unification of perception, planning, and control for physical human robot interaction" (euRobotics AISBL, 2014, p. 133) applies more broadly to functioning in unstructured environments. The challenge could have nothing to do with human interaction but rather (to take an example shared with us by a manufacturing systems research manager at a large U.S. automaker) with "flexible end-effector servo-driven locating and clamping." The capability to assimilate various sensor inputs and to reason what to do (how, for instance, to incorporate sensory input into motion planning for moving an arm or grasping an object) may depend on "standard perception engines for sense data types and sense data fusion" (euRobotics AISBL, 2014, p. 164).

euRobotics AISBL (2014) suggests that KR&R has many potential applications for robotics. Examples include "the representation of higher level concepts in semantic maps, and the use of ontologies to enable robots to elicit information from the Web" (p. 171).

Sensing and perception for unstructured or semi-structured environments is critical to safe HRI. Furthermore, sensing and perception data can be used to optimize robot movements and feedback data into simulation models.

3.2.3 Objective, Low-Cost Performance Characterization

The lack of objective data characterizing the performance attributes of advanced robotic systems is an inhibiting factor to their adoption, particularly for SMEs that are less likely to be able to bring multiple robot technologies in house for internal evaluation and comparison. There is a need for objective evaluation using common benchmarks, testbeds, test protocols, and metrology with traceability to standards maintained at national laboratories.

End users would like to refer to objective data on the performance of systems subjected to standard test procedures or in standard testbeds that model a factory environment similar to theirs. For example, the performance of a robotic arm can be described in terms of its repeatability (of 0.1 millimeter, for example) and accuracy (of 0.5 millimeter, for example).[33] These metrics are commonly understood and sufficient to describe the capabilities of a robot's arm, but there are presently no such standard metrics for the performance of robotic hands. What are the metrics (analogous to repeatability and accuracy for robotic arms) that are relevant for describing the dexterity of a robotic hand?

Low-cost performance characterization also includes related automation systems such as control systems that commonly interact with robots. Other areas where performance may be difficult to characterize include sensing and perception, autonomous mobility, wireless data transmission, safe HRI, and energy efficiency. One observer pointed out that the energy efficiency of robotic systems is less easily characterized than that of, say, an electrical appliance. The efficiency of the robot

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[33] Repeatability can be defined as the ability of a robot to achieve repetition of the same task. Accuracy is the error between the desired task and the actual task obtained by the robot (Joubair, 2014).

will depend on its programming and the conditions under which it is used. This issue raises the need for sophisticated testbeds and test methods that can provide users with relevant insight into a new technology's expected performance under realistic factory conditions.

3.2.4 Interoperability and Modularity

The lack of interoperability across the robotic systems of different vendors (and among robots, machine tools, control systems, and sensors) is costly to end users and inhibits the adoption of advanced robotics technology.

As one developer described, "Getting the robotic arms and end effectors from any manufacturer to work and communicate easily would be a big step toward broader adoption." One collaborative robot manufacturer described lengthy efforts to persuade a single supplier of end effectors to adhere to a specific gripper schematic. The supplier was hesitant perhaps because other customers followed different schematics. An industry standard (de facto or established) would help solve this issue. This sentiment was noted more generally as applied to other peripheral devices, such as vision systems. Every interviewee who made this point agreed that an analogy to USB devices was appropriate. Many added that robotics does not yet have true plug-and-play capability (which most now take for granted when purchasing a printer or camera to attach to a laptop), but having such capability would be valuable to end users.

However, companies that develop industrial robots may have incentives to limit interoperability due to customer lock-in. One developer candidly pointed out that the benefits of interoperability to end users would outweigh any cost of standardization to robotics manufacturers. One gripper manufacturer in particular noted that no single company can do this alone. Lock-in and market power are problems of proprietary standards. Public standards eliminate this barrier to innovation, and NIST, as well as other organizations such as the Institute of Electrical and Electronics Engineers (IEEE), could have a potential role to play in accelerating public standards.

In addition to standards for physical and electronic interfaces, interoperability requires standard software interfaces, or translators. Each robotic system manufacturer has its own programming language. This complicates the integration of many pieces of automated equipment into a production line, making it more costly and time consuming to set up each line. A research team leader at a heavy equipment manufacturer described the problem of having to write XML[34] code to allow an Ethernet-enabled robotic platform to communicate with an MTConnect-enabled[35] machine tool as "not difficult but a hassle." Although this company was large enough to have at least one full-time employee with such expertise, many SMEs would have to hire contractors to perform such work. The need for specialized expertise and training increases the cost of setting up a new line with robotics, making it impractical to automate some production activities that involve small batches and frequent line changes.

An example of a common language standard that allows different robots to communicate and share data is PackML,[36] which is used primarily for automated packaging. It is a communication protocol, analogous to an Internet protocol, like IPv6. MTConnect is another example of such a communications protocol, ostensibly capable of facilitating plug-and-play interconnectivity between robots, machine tools, sensors, and other devices. An engineering manager at a heavy equipment manufacturer described MTConnect as being useful in conjunction with production monitoring systems (like SCADAware and Freedom eLOG) but subject to limitations (e.g., handling data updates in the seconds range, whereas programmable logic controllers in machine tools handle data updates in the submillisecond range). The need for interoperability also extends to the connection of robots with other software and enterprise systems such as manufacturing enterprise solutions systems, enterprise resource planning systems, and programmable logic controllers. Increased interoperability reduces costs for end users and allows for a more competitive, more innovative marketplace.

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[34] XML is an acronym for Extensible Markup Language.

[35] MTConnect is an acronym for Machine Tool Connect. The MTConnect standard enables production machines, sensor packages, and other manufacturing equipment to provide data in standardized formats rather than proprietary formats.

[36] PackML is an acronym for Packaging Machine Language.

The broader vision of those in industry is toward open architectures and standard interfaces to enable the modular construction of systems and the development of a component marketplace. euRobotics AISBL (2014) points toward “modular system architectures with well-defined interfaces” and “architectures based on multifunctional sub system blocks, for example allowing integrated sensing and actuation or multi modal sensing” (p. 124). Modularity will enable scalable, reconfigurable, and reusable robotic systems (as opposed to process monuments). One benefit of modularity will be to reduce the cost of retooling (changing machinery, fixtures, and tools to produce a different model vehicle, for instance). In the automotive and heavy equipment industries, retooling represents a significant cost, which could be reduced by increasing the adaptability of robotic systems. In industries where smaller production runs and frequent line changes make the cost of retooling prohibitive to automation, modular robotic systems that lower retooling cost could make automation cost-effective and lead to greater adoption.

euRobotics AISBL (2014) asserts, “Formalisms and algorithms over different modules (perception, planning, learning, envisioning etc.) are typically incompatible. The top-performing state-of-the-art modules are often the hardest to integrate, because they use sophisticated and incompatible representations and algorithms that must first be adapted to the needs of robot control” (p. 116).

ROS-I is an effort to enhance automation interoperability by allowing robots, manipulators, end effectors, sensors, mobile platforms, and other devices to communicate with one another using a single language. Consortia in the United States and Europe have formed to support the further development of ROS-I. The U.S. consortium includes large end users like Boeing, Ford, BMW, Caterpillar, and 3M, as well as prominent developers such as Yaskawa Motoman and Siemens. NIST is also a member of that consortium.

ROS-I represents an important infrastructure element that supports interoperability robotics and automation systems. However, individuals have pointed out several limitations to ROS (see Section 7.2).

3.2.5 Intuitive Interfaces

One factor contributing to the time required to set up an automated line is programming the robots. We heard from many interviewees that the time and cost of setting up an automated line could be reduced significantly if robots could be programmed more intuitively, without the need to write many lines of code. Intuitive interfaces would allow individuals without specialized training to effectively commission a robotic system.

One setup model involves a person manipulating the robot through the required motions so that the robot is then able to replicate the motions autonomously (e.g., Rethink Robotics' Baxter). Another approach involves an intuitive graphical user interface (GUI) that allows robots and conveyors to be integrated with drag-and-drop instructions, with code auto-generated in the background (e.g., ABB's PickMaster).

One may think of GUI applications that allow an individual to build a query of a relational database by selecting tables and connecting them with lines. The SQL[37] code is generated without the user having to write a line of code by hand. Similarly, one can build a Web page using a GUI interface that writes HTML code in the background. There is presently no standard programming language for robots in general analogous to SQL or HTML on which to build intuitive interfaces.

The ROS and ROS-I provide an open-source software platform with basic functionality. One developer described how his team had written what is called a *ROS bridge* to allow communication between ROS and the proprietary system of a large robotics manufacturer. Criticisms of ROS include that it is trying to solve too many issues at once, that it is currently more academic than industrial in nature, and that there are challenges with its ability to function with real-time fidelity.

3.2.6 Modeling and Simulation

Advanced robotics and automation systems play an important role in smart manufacturing systems. This linkage was most evident in conversations with interviewees from an automaker and a heavy equipment manufacturer who described similar visions for having the ability to virtually model and physically

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[37] SQL is the acronym for structured query language.

control processes on the factory floor from a central dashboard. The virtual modeling environment would accurately emulate the physical manufacturing floor before any robots, machine tools, conveyors, sensors, and other devices and structures were in place. Then, after putting the equipment in place, the virtual models would receive real-time data from the physical manufacturing process to refine the simulations and improve the accuracy of their predictions.

In this scenario, potential adjustments (such as moving a weld point, changing a process to accommodate a change in a supplier's part, or reallocating work when a robot has a mechanical problem) can be simulated, and an optimal solution can be implemented on the plant floor in real time, with minimal delay or work stoppage.

With reference to the automotive industry, to change from the production of one model of a vehicle to another for instance, the time and cost of retooling could be reduced by orders of magnitude if modeling and simulation capabilities allowed the factory floor to be software reconfigurable.

For this scenario to be realized, robots, machine tools, sensors, and control systems must be able to communicate. A research manager at a large automaker emphasized the need for an "open, real-time operating system on the factory floor." For an in-depth exploration of these issues, see the companion report titled *Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing: Smart Manufacturing Processes*.

One expert from the aerospace industry indicated there may be several benefits to measuring what is occurring in the physical world and then replicating that information in the digital world. For aircraft manufacturing, the as-built documentation is important, and a digital representation of the physical aircraft adds value. Being able to simulate tool paths is important to this documentation. Another benefit of enhanced simulation is being able to flow back some of the robot teaching that is done through programming or teach pendants to the central simulation program. This is one way to avoid having to solve the same problem multiple times, and it enables a more accurate simulation.

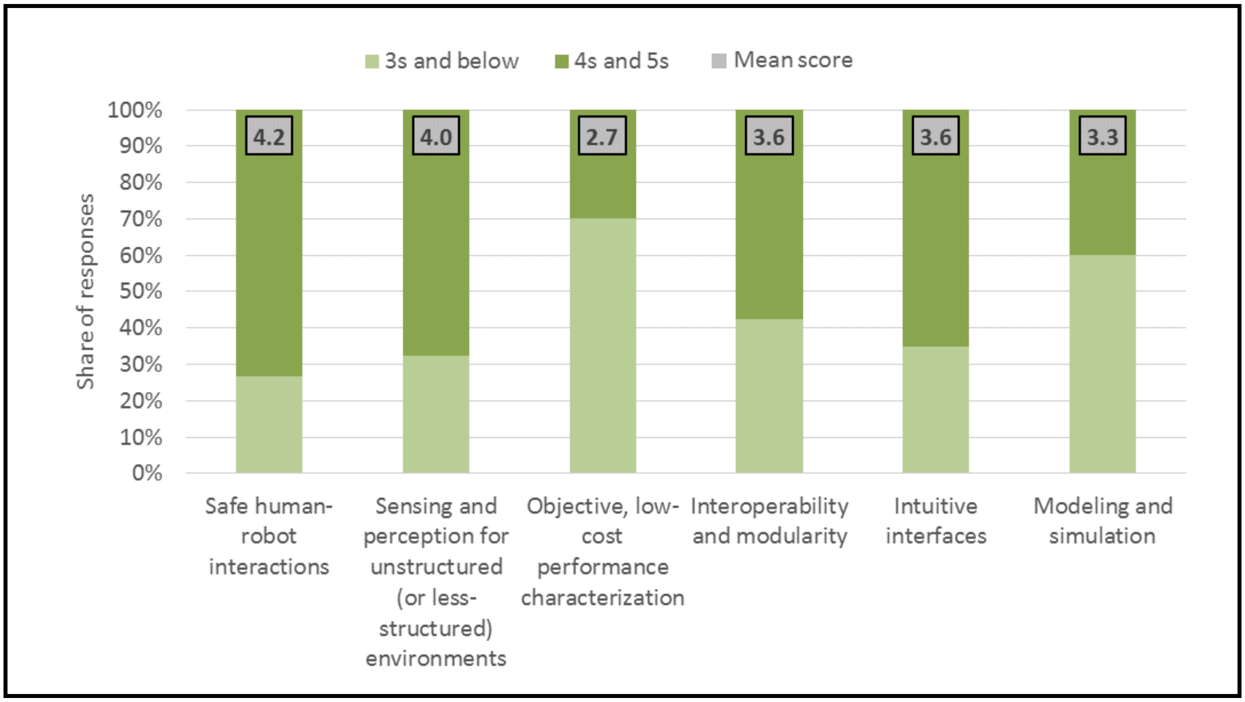
3.3 THE IMPORTANCE OF INFRATECHNOLOGIES TO SUPPORT ROBOTICS AND AUTOMATION

To provide a barometer for NIST in terms of how it might be able to accelerate the development and adoption of robotics technology most effectively, interviewees were asked to characterize the importance of each of the six capabilities in Table 3-2 and corresponding infratechnologies. Safe HRI, sensing and perception for unstructured environments, intuitive interfaces, and interoperability and modularity appear to be the most important needs, whereas the interviewees evaluated modeling and simulation and objective, low-cost performance characterization as noticeably less important.

Following this question, interviewees were asked what they viewed to be the appropriate role for the public sector, including potential roles for NIST, if any, to deliver these capabilities. Figure 3-5 summarizes the responses about the level of importance (measured as 1–5, where 1 represents the least important and 5 represents the most important) by capability. The percentage of interviewees who responded with a 4 or 5 are in darker shades, and the percentage of interviewees who responded with a 3 or below are in lighter shades. The average importance score is overlaid in the gray boxes.

For example, for the capability of safe HRI (the leftmost bar), the lighter portion of the bar represents the 27% of interviewees who responded with a 3 or below, and the darker portion of the bar represents the 73% of interviewees who responded with a 4 or 5. The gray box represents the overall mean importance score of 4.2.

Figure 3-5. Importance of Capabilities/Needs and Corresponding Infratechnology Needs

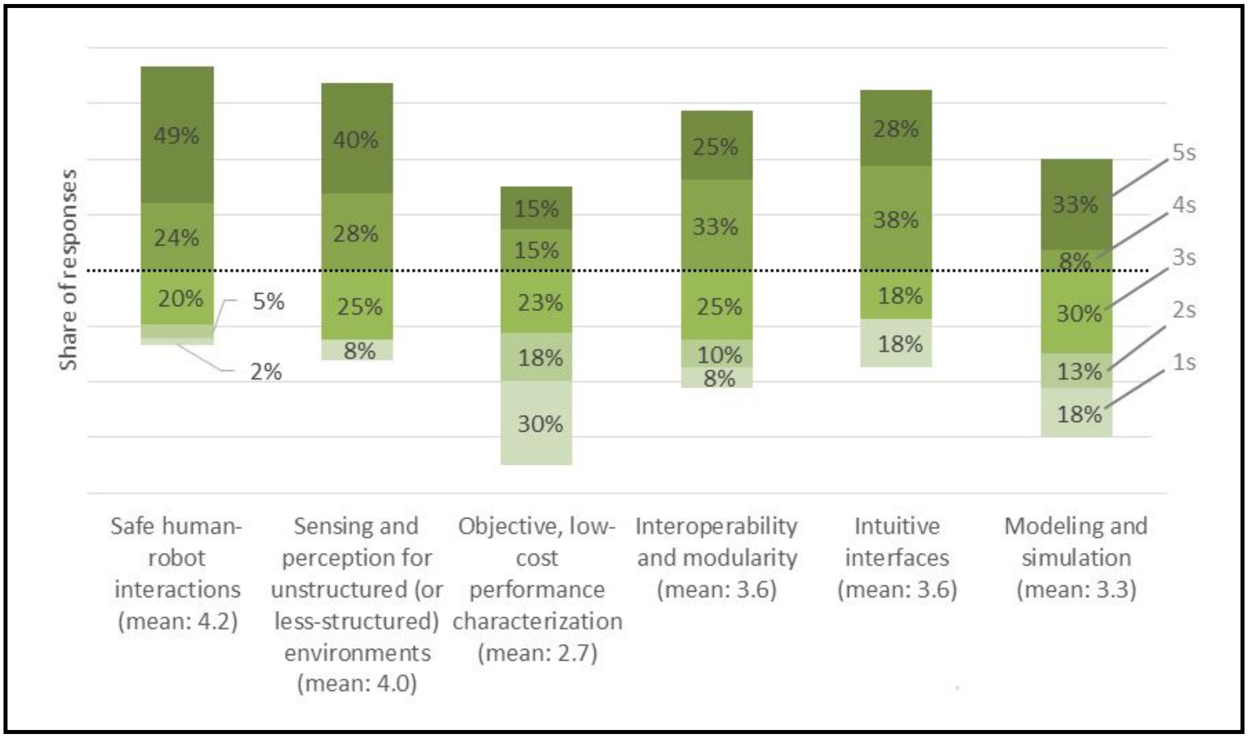


Note: The level of importance of each capability is measured on a scale from 1 to 5, where 1 represents the least important and 5 represents the most important.

If we interpret "important" as a 4 or a 5 and "not important" as a 1, 2, or 3, then the diverging stacked bar chart (Figure 3-6) is an alternative way to visualize the importance scores that draws more attention to the relative sentiment across the six technical areas. The bold horizontal axis represents the baseline between scores of 4 or 5 and scores of 1, 2, or 3. The vertical axis represents the percentage of responses, where each increment represents 20%.

For example, for the capability of safe HRI (the leftmost bar), the lighter portions of the bar that lie below the bold horizontal axis represent the interviewees who responded with a 3 or below, and the darker portion of the bar that lies above the bold horizontal axis represents the interviewees who responded with a 4 or a 5.

Figure 3-6. Importance of Capabilities/Needs and Corresponding Infratechnology Needs, Diverging Stacked Bar Chart



Note: The level of importance of each capability is measured on a scale from 1 to 5, where 1 represents the least important and 5 represents the most important.

As reflected in the distribution of importance scores in the figures, the majority of interviewees evaluated safe HRI, sensing and perception for unstructured environments, intuitive interfaces, and interoperability and modularity as being important; that is, they evaluated the importance of the capability with a 4 or a 5. The interviewees evaluated modeling and simulation and objective, low-cost performance characterization as noticeably less important.[38]

There is some degree of overlap between these capabilities. For example, technology infrastructure that supports objective, low-cost performance characterization can also make it more feasible to implement safe HRI. Several interviews noted interdependence among all of these capabilities. For example, modeling and simulation tools can support safe HRI. Another interviewee stated that better interoperability and modularity would unleash innovation in sensing and perception.

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[38] Appendix C has the importance scores broken out by developers and end users.

Nevertheless, the level of importance of these capabilities might be viewed as a second-order indicator for the areas in which NIST can play a role in advancing the development and adoption of robotics technology. Perhaps a first-order indicator is the comments from interviewees on a potential role for NIST involvement to lead, coordinate, or encourage development in each of these areas. Sections 5–10 describe specific potential actions for NIST to enhance technology infrastructure so that the benefits of robotics are fully realized.[39] Before discussing roles for NIST, we quantify the economic impacts of realizing the needed capabilities through enhanced technology infrastructure.

3.4 STAKEHOLDERS IN ROBOTICS AND AUTOMATION

RTI developed a list of stakeholder groups to interview for our study in order to understand industry perspectives from different parts of the value chain, industry capabilities/needs, and associated infratechnology needs identified in Table 3-2. We also used these interviews to identify barriers inhibiting the development and adoption of robotics technology in manufacturing. In developing these stakeholder groups, we considered the structure of the robotics industry as it relates to manufacturing and the potential trajectory of the industry.

Table 3-3 shows the number of observers, developers, system integrators, and end users with whom we spoke for this study. The perspectives that each stakeholder group represents are discussed as follows.

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[39] Each of the six capabilities is discussed in the order of the highest stated importance to the lowest stated importance.

Table 3-3. Number of interviewees by Position in the Value Chain

Stakeholder	Subcategory	Number of Interviewees
Observers	**Industry associations**	**5**
	Universities and research centers	**7**
	Other	**4**
Developers	**Robotic systems**	**16**
	Industrial robots	7
	Collaborative/mobile robots	8
	Robotics hardware components	**7**
	End effectors/grippers	6
	Vision systems	2
	Robotics software	**8**
	Industrial automation	**3**
System Integrators		**4**
End Users		**30**
	Aerospace	5
	Automotive	10
	Electronics	4
	Metal products	6
	Process	3
	Other discrete parts	2
Total		**84**

Note: The number of interviewees reflects unique interviewee-interview instances.

3.4.1 Observers

Industry observers, such as those in industry associations and university research centers, provide valuable information about the trends in robotics and the potential impacts of improved infratechnology across manufacturing industries. For example, one industry observer had more than 3 decades of experience working with developers and end users in the robotics industry and had witnessed the industry evolve.

Observers often interact with developers and end users across multiple manufacturing industries. Observers are sometimes reluctant to provide quantitative estimates of economic impacts; however, they do provide rich qualitative insight. Although observers do not account for a large portion of our 84 interviews, they provided important, broad-based insight about customer needs and technical challenges. Therefore, most observers were interviewed from the perspective of a developer.

3.4.2 Developers

From the developer stakeholder group, we learned how enhanced infratechnology will affect the R&D process and enable new capabilities and use cases for customers. Developers would be directly using the technology infrastructure and technology platforms that NIST could potentially provide or work to ensure that they are provided by other entities. Some of the developers also provided insight from the end user perspective because they work closely with end users in solving technical challenges.

Developers include companies manufacturing and selling entire robotic systems and robotics hardware components such as robot arms and end effectors. These companies—which comprise 41% of our interviews—are intimately familiar with the current state of the art of robotics technology. They perform in-house R&D to improve the capabilities of their robots and use technologies in the public domain to meet their new product development goals.

Other developers focus on robotics software tools. Interviewees suggested that some software development for industrial robots (especially algorithms for safe HRI) is performed in universities and nonprofit consortia, so we also reached out to researchers in these settings for additional information.

Finally, developers such as robotics R&D companies and research institutes focus on applied and long-range R&D.

3.4.3 System Integrators

System integrators have a unique perspective because they often work across multiple industry sectors and use multiple robotics vendors. They represent an important bridge between developers and end users, and they play an essential role in customizing solutions, although as one industry expert pointed out, integration of robotics as a practice has not been standardized: “Integrators consider every project as a new project. Smaller companies are creating the solutions. There is no standardized approach to integration, no intellectual bandwidth for R&D on the solutions side.” Integrators understand the technical pain points faced by end users that infratechnologies could improve. At the same time, integrators have some influence on how new technologies are adopted and used. Integrators were interviewed from the perspective of end users.

There is some degree of vertical integration in the robotics value chain; some of the major robot suppliers also provide integration as a service, and some of the more sophisticated end users also do their own integration. As has been discussed in this report, it is possible that integrators will play less of a role moving forward as collaborative robots are adopted.

3.4.4 End Users

A large portion of our interviews were targeted at end users. This population includes companies that use robotics and automation in their operations and that could benefit from the additional capabilities that the next generation of advanced robotics technologies will provide. This population also includes manufacturing companies that sparingly use the current generation of traditional industrial robots but could potentially use the next generation to a greater extent given its increased capabilities. In both cases, we sought to understand the capabilities and supporting infratechnology that would be needed to enable new applications.

Specifically, for current users, we sought to understand the limits of existing robotics technology and the applications of the new technologies enabled by the infratechnologies discussed in the interview process. For non-users, we sought to understand the barriers to development and adoption of new technologies and how advanced robotics will affect the cost structures of existing industries.

RTI focused on end users in the manufacturing sector.[40] The manufacturing sector comprises establishments that carry out mechanical, physical, or chemical transformation of materials, substances, or components into new products, or

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[40] Although outside the scope of this study, several interviewees noted that service robotics and consumer robotics, while not as far along in terms of market adoption, are much larger markets than the manufacturing robotics market. One interviewee compared the current robotics market to the personal computing market before PCs were adopted by households, which came much later than the business sector's adoption of computers.

establishments that assemble component parts into new products (U.S. Census Bureau, 2012).[41] End users span all organization sizes, from small job shops to multinational Fortune 500 companies.

Our coverage for advanced manufacturing robotics and automation includes the end users in aerospace, automotive, electronics, metal products, process, and other discrete parts manufacturing. Table 3-3 shows the count of end users with whom we spoke, by industry group. These groups are based on industries having the same value chain (e.g., aerospace, automotive) or industries having similar production processes (e.g., electronics, metal products, process, other discrete parts manufacturers).

Overall, speaking with stakeholders from various parts of the robotics and automation value chain provides us with a well-rounded view of market trends, barriers to development, barriers to adoption, and the infratechnologies that NIST can provide to support the needed capabilities outlined in Table 3-2.

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[41] In terms of the NAICS, manufacturing includes sectors 31, 32, and 33. By this definition, the extraction of natural resources, agriculture, and construction are out of scope.

4 Quantitative Results and Economic Impact Analysis

Based on interviewee responses, we estimate that enhanced infratechnology for robotics and automation would result in $40.4 billion in net cost savings for the U.S. manufacturing sector compared with current baseline national factor expenditures on four factors of production—capital, labor, energy, and materials (KLEM). These aggregate cost savings represent a 5.3% decline in shop floor KLEM expenditures across the aerospace, automotive, electronics, metal products, process, and other discrete parts manufacturing industries. These savings are concentrated in labor and materials, which are partially offset by an increase in capital expenditure for robotics and automation technology.[42] Next-generation robotics and automation technology will make U.S. manufacturers more efficient and more flexible, making the U.S. manufacturing sector better positioned to compete internationally, which is a policy goal of the White House and federal agencies.

Developers will measure benefits in terms of the increased penetration of their technology in the marketplace. Robot suppliers and service providers believe that enhanced infratechnology will lead directly to increased demand from end users and thus increased sales. The RIA estimates the U.S. robotics market at $1.5 billion in sales in 2014 (RIA, 2014). Accounting for ancillary products and services—which are roughly two times the number of sales shipments—the overall market for robotic systems in the United States is roughly $4.5 billion. Based on responses from interviewees, the U.S. robotics

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[42] Energy costs are expected to increase as well because of the increase in the stock of robots, but these costs are negligible.

market would grow by 48% if enhanced infratechnologies were in place. Accounting for ancillary products and services, the overall market could increase by as much as $2.1 billion. This figure is not included in the overall economic benefit because it represents a transfer of surplus from end user manufacturers to robot developers, the net social benefit of which is zero. Nevertheless, the expected growth illustrates that enhanced infratechnology could substantially influence the adoption of robots.

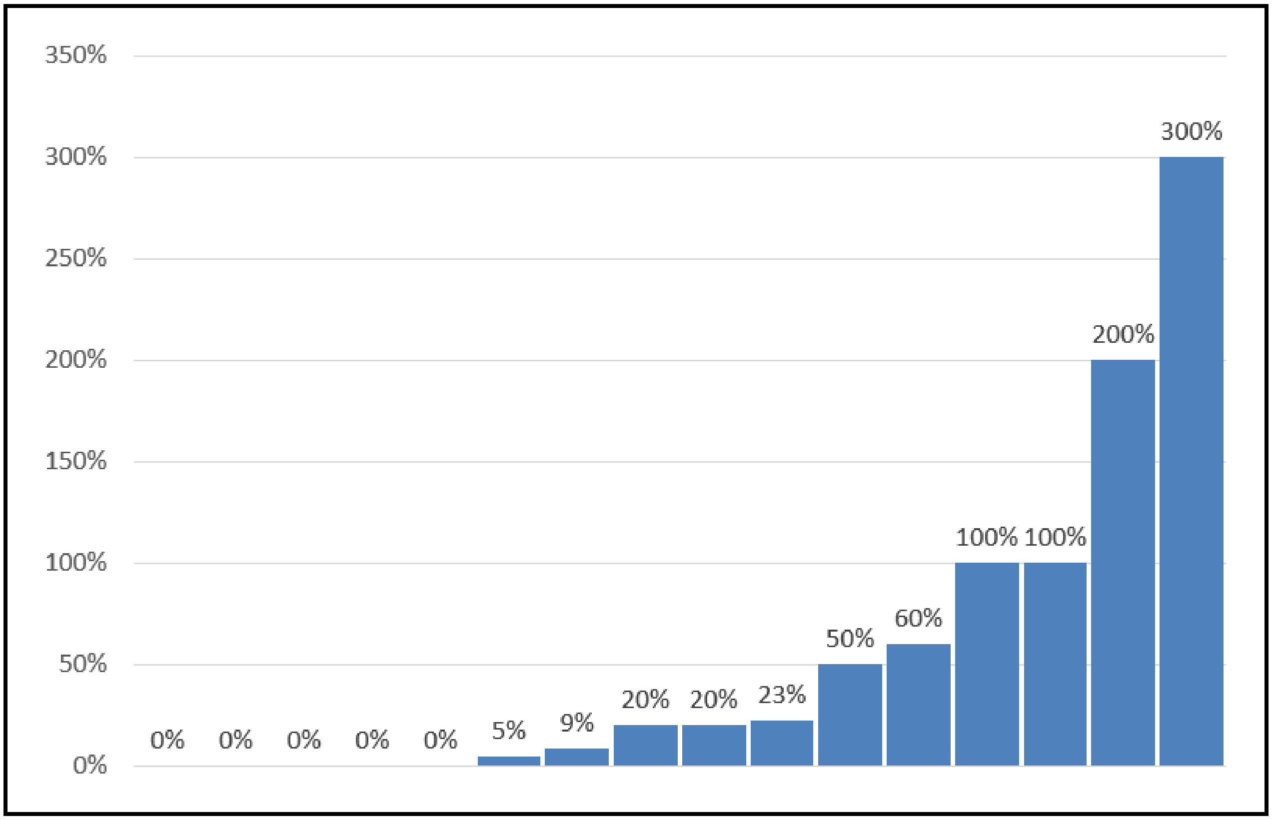
4.1 FIRM-LEVEL DEVELOPER SALES IMPACTS

Developers of robotics and automation technology also stand to benefit from enhanced infratechnology in terms of increased market opportunities. Many developers with whom we spoke are able to make a direct link between enhanced infratechnology and increased sales of robotics technology because enhanced infratechnology would lead directly to increased adoption of robotics and automation.

For example, SMEs—which are more likely to use collaborative robots than traditional industrial robots—represent a largely untapped customer base. Also, large industries such as the aerospace sector have a lot to gain from enhanced infratechnology because robotics are typically used only at early stages of the production process (see vignette in Appendix D). Aerospace manufacturing does not have the repeatability of the automotive sector, which has limited the uptake of traditional industrial robotics in aerospace manufacturing, but one can envision many use cases in the aerospace sector where more flexible robotics technologies could be deployed.

On average, developers cited a 55% increase in their sales that would be directly attributable to enhanced infratechnology in the six areas outlined in Section 2. Figure 4-1 shows the distribution of percentage changes in sales, which varies from 0% to 300%.

Figure 4-1. Percentage Change in Developer Sales Associated with Enhanced Infratechnology



Note: Each vertical bar represents one interview response.

4.2 NATIONAL-LEVEL DEVELOPER SALES IMPACTS

Scaling sales impacts up to the national level first requires adjusting the impacts by using the industry applicability factor that each interviewee provided. The average applicability-weighted sales impact is 48%. This percentage should be interpreted to mean that the robotics market would grow by as much as 48%. NIST provided the underlying infratechnologies to enable the capabilities outlined in Table 3-2.

4.2.1 Market Size

As mentioned in Section 3.1, 25,425 robots were sold to companies in North America, yielding $1.5 billion in revenues for robotics suppliers in North America. This represents roughly 14% of the global market in 2014.

To account for ancillary services and products such as integration, systems engineering, peripherals, and software, we used a standard 3X multiplier to calculate the total size of the market, which is what IFR uses in its statistical reports. We believe the 3X multiplier is conservative based on information from our interviews with stakeholders.[43]

4.2.2 Total National Impacts for Developers

We estimate a $2.14 billion increase in U.S. sales of robotics technology because of enhanced infratechnologies.[44] If the infratechnology needs were met today, the increase in sales is likely to occur over an approximately 5- to 10-year horizon as infratechnologies diffuse among market participants. Most of this increase is likely concentrated in the manufacturing sector, although some developers whom we interviewed sell to multiple sectors, and enhanced capabilities for manufacturing will have spillover benefits for other sectors.

Of the $2.14 billion increase, $713 million is presumed to be shipments of robot systems, whereas $1.4 billion is presumed to be ancillary products and services. Based on our sample of interviews, we expect significant purchasing to take place in the aerospace, automotive, and metal products sectors based on the expected benefits in these industries.

4.2.3 Other Impacts Not Quantified

Other developer impacts that have not been quantified in this study include the impact of technology infrastructure on R&D costs, R&D opportunities, accelerated improvement of existing products, and accelerated development of altogether new products.

Interviews suggested that, in fact, there would be real impacts in some of these areas if industry needs were met through enhanced technology infrastructure such as standards. However, limited quantitative information was provided in the interviews. Some developers said that their overall R&D budgets would not be reduced, but instead that it would free

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[43] It is possible that the multiplier to arrive at the overall system cost could decline over time. However, we did not specifically ask interviewees about the impact that improved technology infrastructure would have on this variable. We believe that the 3X multiplier is reasonable and conservative.

[44] To calculate the national impact on sales for developers, the following calculation was done: $1.5 billion U.S. market for robots x 3X multiplier = $4.5 billion market, including ancillary products and services x 48% = $2.14 billion increase in market revenues.

them up to work on other things. Other developers suggested marginal decreases in costs but struggled to quantify them. Other interviewees suggested that R&D opportunities (the likelihood of technical success) would increase because everyone in the industry would be “playing by the same rules.” Furthermore, interoperability would help companies improve existing technologies and develop new technologies more rapidly because less time would be spent translating between systems and more time could be spent creating new interfaces.

4.3 FIRM-LEVEL END USER IMPACTS

During our interviews, respondents were asked to estimate the percentage change in KLEM factor inputs resulting from the potential adoption of improved robotics and automation manufacturing technologies, as well as impacts on products. Individual firm-level impacts are then aggregated and scaled to estimate potential national-level economic impacts.

Table 4-1 shows the average percentage change in factor inputs provided by respondents. Not surprisingly, robotics has the potential to reduce labor substantially: by 18%. The net percentage change in capital was positive, suggesting that end users think that enhanced robotics technology will result in increased purchases of robots. Note that the percentage change in capital costs reflects net capital expenditures, which include additional capital expenditures to implement robotics and capital savings due to increased efficiency. The average materials savings due to enhanced robotics and automation technology was 8%. Energy costs had a negligible increase on average, reflecting that more robots would need to be powered.

Table 4-1. Percentage Change in Factor Inputs Due to Having Industry Needs Met

Factor Input	Mean Impact of Having Industry Needs Met
K: Capital	+22%
L: Labor	−18%
E: Energy	+1%
M: Materials	−8%

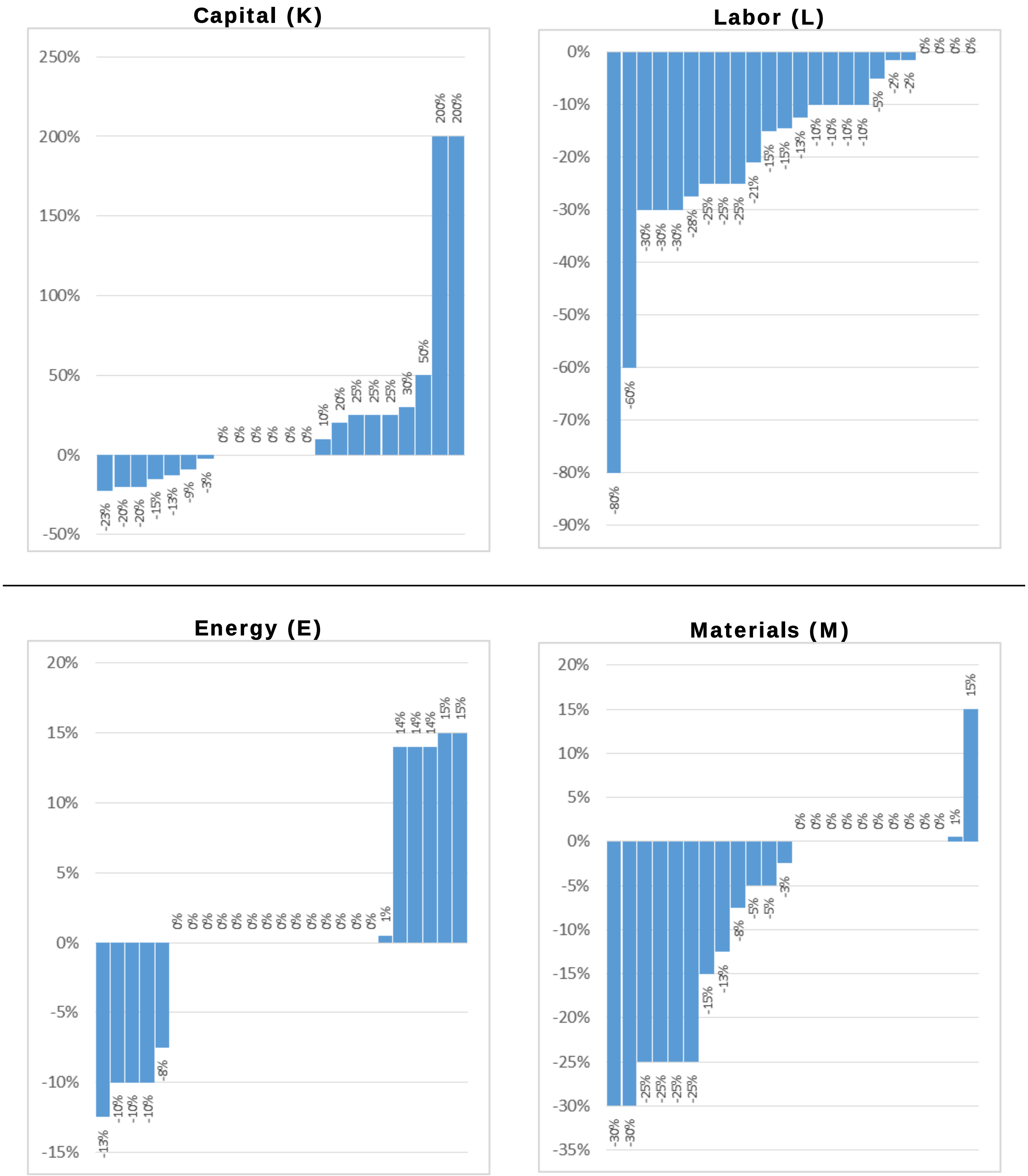
Figure 4-2 shows the range of the raw responses from interviews broken out by each factor of production. For example, the top left panel represents the individual percentage responses about the impact on infratechnologies on capital costs. A few stories emerge from the panel of graphs. On average, capital costs tend to increase, but the figure indicates that in reality, the impact is much more nuanced and depends on the firm. One group of firms expects that capital costs will increase on net as more robots are purchased. Other firms expect that although more robots will be purchased, other forms of more expensive capital will be more efficiently used because of the benefits that robots provide, which drives down capital costs on net. Yet another group of firms expected no net change in capital costs.

In terms of the labor input, it is clear that robotics and automation technology reduce labor costs. This occurs through the reduction of workers needed or through the increased productivity of existing workers, although long-term manufacturing trends indicate that the U.S. manufacturing sector continues to produce more output with fewer workers. Ergonomically stressful or monotonous jobs are often the first ones that are targeted to be automated because of worker safety and quality concerns and associated costs.

For energy, there are three camps of responses. Most companies thought that energy costs would remain unchanged by enhanced robotics and automation. Another group thought that energy costs would be reduced between 8% and 15%. A third group thought that energy costs would increase between 14% and 15% because of the increase in installed robots. Finally, for the vast majority of interviewees, materials costs were expected to decrease or remain unchanged. Reduced rejection rates due to the greater use of robotics is one example of why materials costs would decrease.

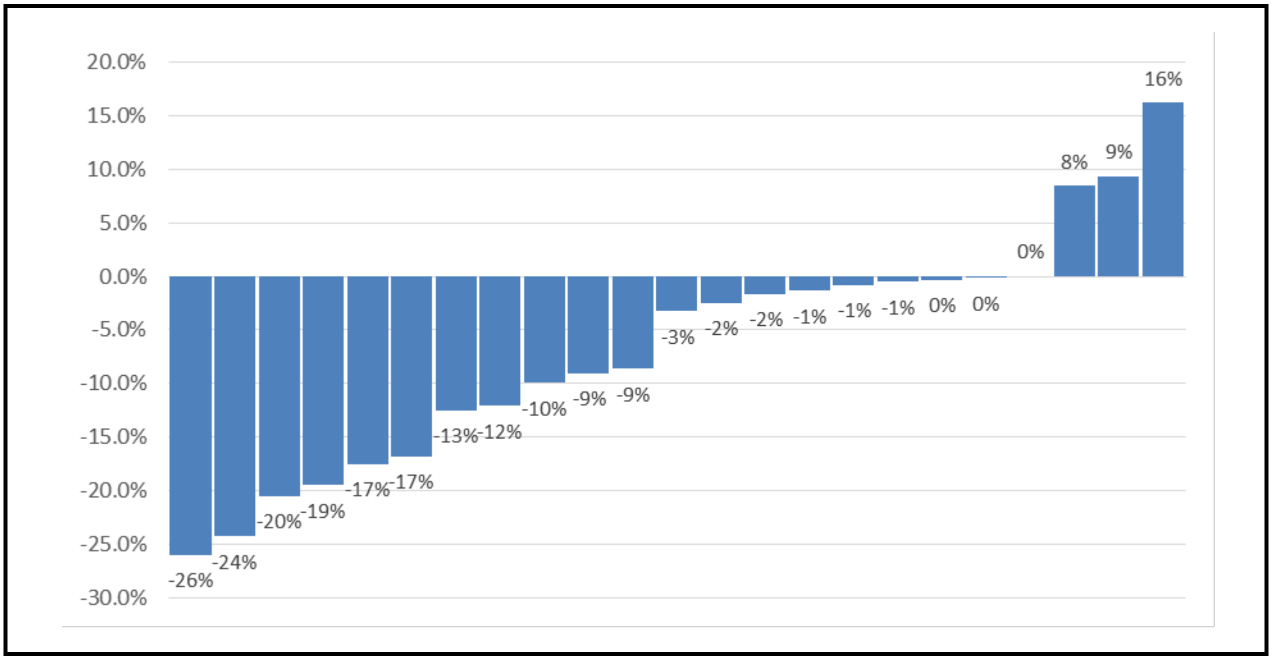
The percentage change in each of the factor inputs is then applied to estimated expenditures on the inputs for each firm to obtain a composite percentage impact on costs. This was conducted for each user interviewed estimating applicable firm-level factor expenditures. Aggregating the firm-level factor impacts yields a single (weighted average) percentage change in production costs. Figure 4-3 shows the firm-level impacts for each respondent.

Figure 4-2. Range of Cost Impacts on Shop Floor Expenditures Associated with Enhanced Infratechnology, by Factor Input



Note: Each vertical bar represents the consensus from each interview.

Figure 4-3. Range of Total Composite Cost Impact on Shop Floor Expenditures Associated with Enhanced Infratechnology



Note: Each vertical bar represents the consensus from each interview.

When accounting for the share of total expenditures on KLEM, the average composite cost impact is a 6.7% reduction. As shown in Figure 4-3, firm-level composite cost impacts vary widely. Although a few of the composite cost impact estimates show net cost increase, this could be the result of industry data not aligning well with individual firms' cost structures or other cost dimensions that we did not capture in our interviews. We have kept these increases in our results so as to be more conservative.

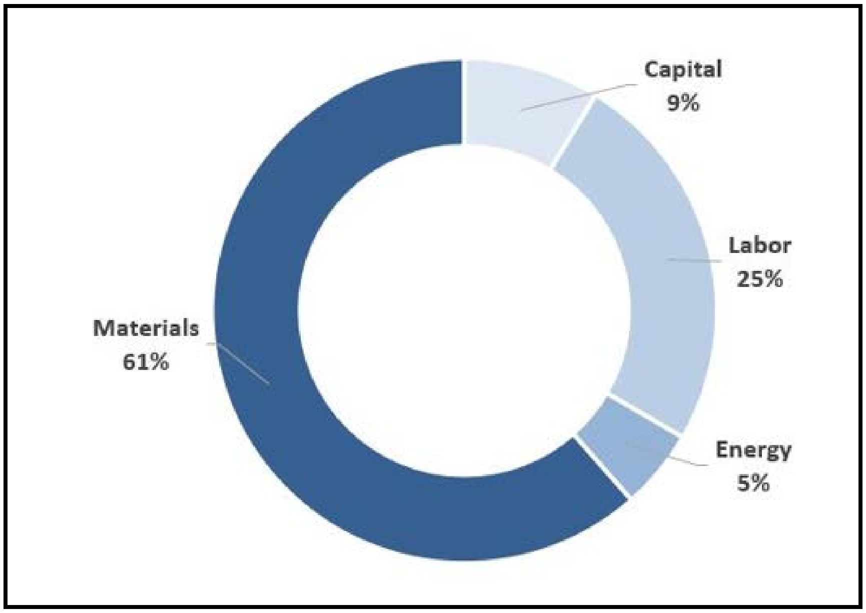
The end user responses described in this section form the foundation for the national-level end user impacts in Section 4.4.

4.4 NATIONAL-LEVEL END USER IMPACTS

Overall, we estimate that enhanced infratechnology for robotics and automation would result in $40.4 billion in cost savings for the U.S. manufacturing sector. This cost savings is driven by the percentage changes from Section 4.3 and the total national factor expenditure represented by the industries in our sample.

As Figure 4-4 shows, materials costs make up the majority of national factor expenditures for the industries addressed by our study. Materials costs are the primary cost driver, accounting for 61% of total national factor expenditure for the industries in our sample. Labor costs and capital costs make up 25% and 9%, respectively. Energy costs make up the remaining 5%.

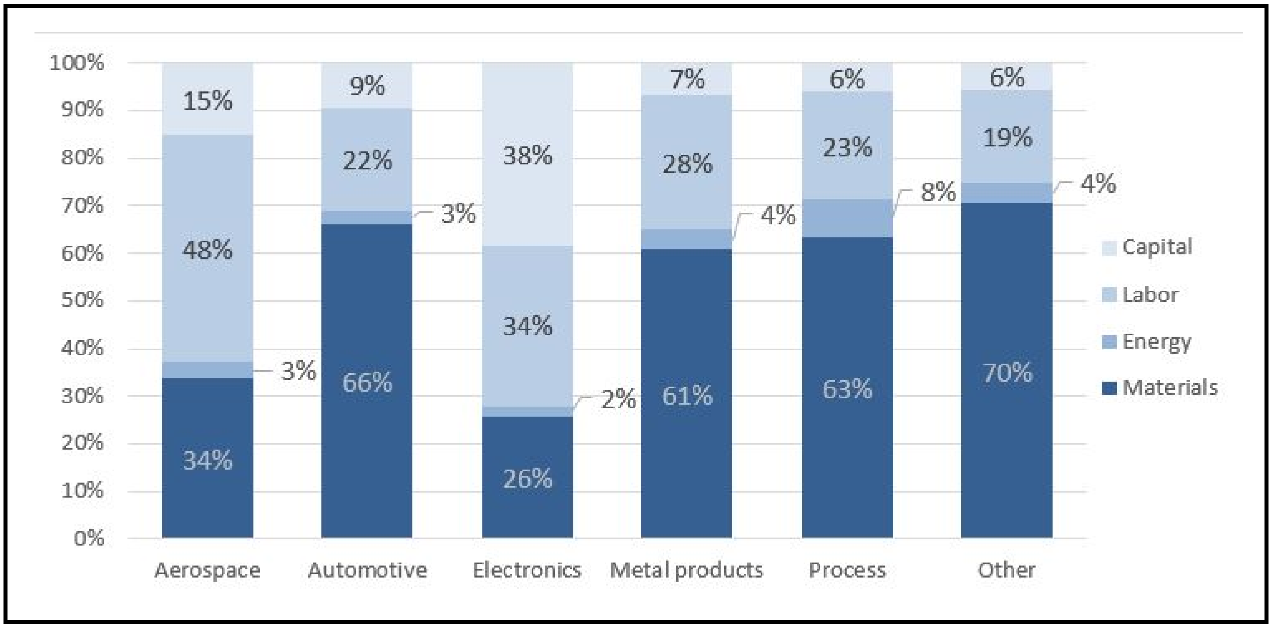
Figure 4-4. KLEM Shares of National Factor Expenditure



The breakdown of costs has implications for our economic models. For example, a 1% cost savings for materials is going to have a greater absolute dollar value impact than 2% cost savings for labor.

The distribution of costs among factors of production varies across industry sectors in our sample. Figure 4-5 shows the share of the national factor expenditures accounted for by each factor input for aerospace, automotive, electronics, metal products, process industries, and the remaining industries in our sample. Electronics manufacturing is substantially more capital intensive than the other industries in our sample. In contrast, aerospace manufacturing is the most labor-intensive industry sector. Finally, automotive and the “other” remaining industries are the most materials-intensive industries.

Figure 4-5. KLEM Shares of National Factor Expenditure, by Industry Sector



Great care was taken to determine the appropriate quantity of KLEM expenditures to which we apply cost impacts, and we defined each factor input to hone in on shop floor expenditures. Furthermore, interviewees answered a question about the share of firms within the manufacturing sector for which the stated cost impacts are applicable. The average applicability factor was 90.1%.

Following the procedures outlined in Section 2, we scaled out sample impacts to the national level using a series of informed assumptions about how the responses in our sample mapped to U.S. industries. Table 4-2 illustrates our calculations with a stylized example for a particular NAICS code. These same calculations were carried out for the NAICS codes in our sample. The estimates for each NAICS code derived in Step 5 in Table 4-2 were then summed together to obtain estimates of national economic impacts.

Table 4-3 shows our results, broken down into the four factors of production. Overall, enhanced infratechnology for robotics and automation would result in an estimated $40.4 billion in cost savings for the U.S. manufacturing sector. This impact is driven by substantial labor and materials savings that are partially offset by an increase in capital investment and energy usage.

Table 4-2. Stylized Example of Scaling Sample Impacts to the National Level, End User

Step	Description	Figures and Calculation(s)
Step 1—Begin with KLEM percentage impact responses.	Percentage changes in KLEM factor inputs are recorded during the interview.	K: +25% L: -10% E: +10% M: -5%
Step 2—Calculate applicability-weighted cost impacts.	Multiply the industry applicability factor from the interview with the percentage changes in KLEM factor inputs to derive the applicability-weighted cost impacts.	Applicability factor = 50% K: +25% x 50% = +12.5% L: -10% x 50% = -5% E: +10% x 50% = +5% M: -5% x 50% = -2.5%
Step 3—Assign an industry code and average responses from the sample.	Assign a 3- or 4-digit NAICS code based on the interviewee's company and average the applicability-weighted cost impacts from Step 2 with other responses from the sample that are categorized with the same NAICS code, if applicable.	The NAICS code that best describes this interviewee's company is NAICS 3329 Other fabricated metal product manufacturing. No other responses in the sample have the same NAICS code, so the average responses are simply the figures from Step 2. K: +12.5% L: -5% E: +5% M: -2.5%
Step 4—Estimate KLEM expenditures for the industry.	Using Annual Survey of Manufactures and Bureau of Labor Statistics data on KLEM-to-sales ratios, estimate the KLEM expenditures for the 3- or 4-digit NAICS code. Sum the individual KLEM expenditures to estimate the total national factor expenditure for the NAICS code.	2013 industry sales from Annual Survey of Manufactures = $75.4 billion K: 2.8% x $75.4 billion = $2.1 billon L: 13.3% x $75.4 billion = $10.0 billon E: 1.7% x $75.4 billion = $1.3 billon M: 31.1% x $75.4 billion =$23.5 billon Total KLEM national factor expenditure = $36.9 billion
Step 5—Calculate KLEM expenditure impacts and composite cost impact on national factor expenditures.	Calculate KLEM expenditure impacts using average percentage impacts from Step 3 and KLEM expenditures from Step 4. Sum together each KLEM expenditure impact from Step 5 to estimate the composite cost impact.	K: +12.5% x $2.1 billon = +$265 million L: -5% x $10.0 billon = -$502 million E: +5% x $1.3 billon = +$63 million M: -2.5% x $23.5 billon = -$586 million Composite cost impact = -$760 million
Step 6—Calculate composite cost impact in percentage terms.	Divide the composite cost impact from Step 5 by the total national factor expenditure from Step 4.	Percentage composite cost impact = -$760 million/$36.9 billion = -2.1%

Table 4-3. Economic Impact Summary Table

	Industry Data, 2013		Cost Impacts, Billions					
	Sales	**Shop Floor KLEM National Factor Expenditure**	**K: Capital**	**L: Labor**	**E: Energy**	**M: Materials**	**Total**	**Percentage Impact**
Total	**$2.13 trillion**	**$759 billion**	**+$11.4**	**-$22.1**	**-$0.4**	**-$29.3**	**-$40.4**	**-5.3%**
Aerospace	$224 billion	$47 billion	-$0.4	-$4.6	+$0.1	-$2.6	-$7.5	-16.0%
Automotive	$542 billion	$190 billion	+$9.6	-$8.8	$0.0	-$12.4	-$11.5	-6.1%
Electronics	$133 billion	$30 billion	+$1.0	-$1.0	$0.0	-$1.8	-$1.8	-5.8%
Metal products	$183 billion	$103 billion	-$0.1	-$4.3	-$0.1	-$3.8	-$8.3	-8.1%
Process	$849 billion	$273 billion	+$0.8	-$3.0	-$0.4	-$8.7	-$11.3	-4.1%
Other discrete parts	$203 billion	$115 billion	+$0.4	-$0.4	$0.0	$0.0	$0.0	0.0%

Table 4-3 also shows the cost impacts for several industry sectors. Despite the fact that robotics and automation are already highly adopted and deployed in the automotive sector, there is still a large potential for new cost savings in that sector. According to our estimates, the aerospace sector, the metal products sector, and the process sector also represent large potential cost savings from enhanced technology infrastructure. In percentage terms, the aerospace and metal product industry sectors represent the largest potential cost savings compared with current national factor expenditures at 16.0% and 8.1% reductions, respectively.[45]

It is interesting to note the differential impacts on the factors of production across the six industries. Specifically, impacts on capital costs vary across the industries. Capital costs are expected to increase substantially in the automotive sector and to a much lesser degree in the electronics and process sectors, whereas capital costs are expected to decrease slightly in aerospace and metal products. Given that responses represent net impacts on costs, the difference in directions could reflect that interviewees did not hold output and time constant. Interviewees from the automotive sector could be interpreting enhanced technology infrastructure as increasing domestic output as U.S. industry becomes more competitive internationally. However, from the data we have collected, it is not possible to determine the underlying root causes of these different impacts.

4.4.1 National-Level End User Impact by Capability

Figure 4-6 shows the distribution of total KLEM impacts apportioned to each of the six capabilities. The distribution of impacts reflects the importance scores provided by end users. Intuitive interfaces, safe HRI, and sensing and perception all have impacts greater than $7 billion. These are followed by interoperability and modularity as well as modeling and simulation, with $6.6 billion and $6.3 billion in cost impacts, respectively. Reflecting its lower overall importance score, objective, low-cost performance characterization has the smallest impacts of all capabilities with $5.4 billion.

A caveat to Figure 4-6 is that there are often strong complementarities or “interaction effects” between capabilities that we were not able to quantify. For example, modeling and simulation tools supporting risk assessment can enable safe HRI. Another example is that improved interoperability and modularity can enable enhanced sensing and perception as sensors, perception equipment, and algorithms are more easily

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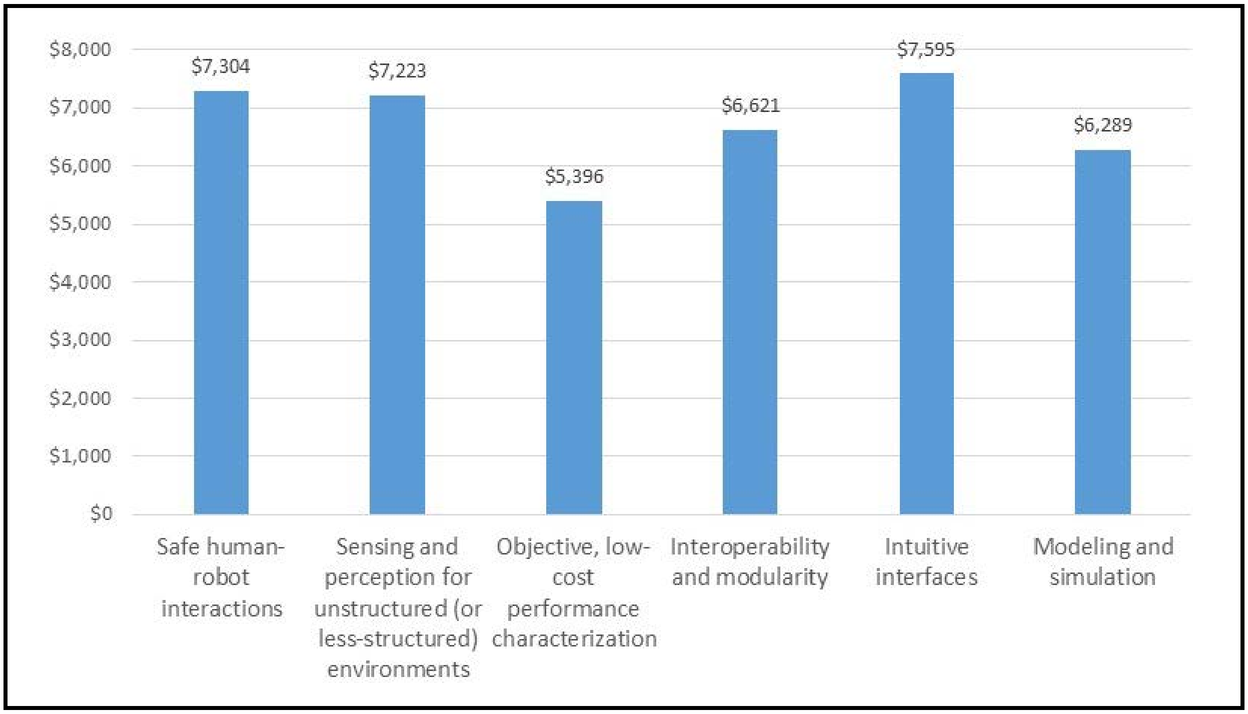
[45] Appendix D contains a vignette of how robotics and automation could transform the aerospace product and parts industry.

Figure 4-6. Total Cost Impact, by Capability (Millions of 2013 US$)



integrated with robotics technologies. To the degree that these complementarities are roughly proportional across the six capabilities, Figure 4-6 represents a reasonable approximation.

4.4.2 Other Impacts Not Quantified

End user impacts that have not been quantified in this study include impacts on production and product offerings.

Enhanced technology infrastructure can impact production through reduced time and/or cost required for workcell setup, reduced unplanned downtime, and reduced product-development-to-production cycles. Likewise, enhanced technology infrastructure can impact end users' product offering by improving the quality of existing products, increasing the amount of customization possible, and accelerating the introduction of new products.

We were unable to quantify impacts of this kind because of limited quantitative information. However, the production impacts are indirectly included in the KLEM impact estimates. Impacts on product offering are not included in this study, which makes the estimates herein more conservative in nature.

5 Safe Human-Robot Interaction

Safe HRI is arguably the most important and potentially transformative of the six needed capabilities for robotics technology. The development and adoption of safe human-robot technology is inhibited by several barriers to innovation (sources of market failure) such as the broad scope of commercial applications that is beyond the reach of any individual firm, technical risk, market risk due to safety issues and cultural acceptance, and difficulty in bringing together component technologies that are necessary for various approaches to safe HRI (see Table 1-2).[46]

NIST can play a role in enhancing infratechnologies by providing standardized risk assessment tools and test methods, creating taxonomies and promoting paradigms of safe HRI, and coordinating with major players that have influence on robot safety standards, among other things.

Finally, the advancement of other needed capabilities such as sensing and perception and simulation and modeling through NIST R&D may serve to augment safe HRI.

5.1 BARRIERS TO INNOVATION AND SOURCES OF MARKET FAILURE

Drawing from the discussion in Section 1.3 and the taxonomy of barriers to developing and adopting new technologies that bring about market failure outlined in Table 1-2, the barriers most relevant for safe HRI are[47]

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[46] From a network externality perspective, this might be referred to as an indirect network effect (Garrell and Saloner, 1985).

[47] The reader should note that the barriers to innovation are different for each of the capabilities discussed in the subsequent sections.

- a scope of commercial applications broader than the market strategy of any one firm;
- the risk that R&D outcomes will be technically insufficient (technical risk);
- the risk that R&D outcomes, although technically sufficient, will gain insufficient market acceptance to provide an acceptable return on investment (commercial or market risk); and
- difficulties in bringing together component technologies from different industry segments.

These barriers are manifested in a variety of ways, but overall, they serve to inhibit the development and adoption of safe HRI technology. Safe HRI will have many commercial applications that extend across multiple sectors of the economy; thus, it is unlikely that any individual firm would be able to appropriate all of the commercial profits. Safe HRI is also characterized by a high degree of technical risk given that it is such a nascent area of research and that existing safety standards are not well understood.

Market risk may be the greatest barrier inhibiting the development and adoption of safe HRI. Market risk includes several dimensions, but perhaps the most important is the cultural acceptance of robots. Many robot suppliers and end users cited this as a challenge. Additionally, to the extent that the United States and global regulatory frameworks reflect cultural values and norms that embrace the status quo, regulations may inhibit development and adoption of robotics technology. Safety standards, when adequate, will influence the adoption patterns of manufacturers by providing greater confidence and thereby increase market demand.

Finally, safe HRI will require the seamless integration of many component technologies such as robot arms, end effectors, vision systems, sensors, robot controllers, and other software. Because of a lack of interoperability and modularity in the industry (see Section 8), it is difficult to bring together multiple component technologies efficiently without a substantial investment of engineering resources.

5.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

More than 70% of interviewees assigned safe HRI an importance score of 4 or 5, indicating that this was a highly important capability. In fact, this score was higher than any other capability about which we asked (see also Section 3.3 for a comparison of score across the six capabilities). Not surprisingly, there were many substantive comments on how NIST could play a role in this technical area. Additionally, developers and end users agreed that this was a highly important need.[48]

Infratechnology needs have been discussed throughout the report, but Table 5-1 summarizes potential roles for NIST, ordered by frequency of occurrence. Of all interviewees, 48% provided at least one potential role for NIST in this area.

5.3.1 Risk Assessment and Measurement Tools

Although the RIA has promulgated safety standards and technical guidance, the interviewees with whom we spoke think that additional work can be done on safety standards to empower manufacturers to apply them. Interviewees stated that it is difficult to implement the standards even with the added benefit of injury data in the new ISO technical specification document. Interviewees suggested that NIST can contribute significantly to the continued development of safety standards and practices by developing and standardizing metrics and test protocols for measuring safety outside of a cage. For example, standardized metrics are needed for measuring pain, force, torque, and risk. Some work is being done in this area already, but NIST can contribute.

As a suite of metrics and test protocols starts to emerge, manufacturers require tools for performing streamlined risk assessments that reduce the need for integrators. The cost of integration can often act as a barrier to adoption because the up-front costs associated with integration are high. Thus, streamlined tools for risk assessment in collaborative robot applications involving safe HRI could accelerate the adoption of robots.

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[48] End users slightly preferred intuitive interfaces.

Table 5-1. Technology Infrastructure Needs Related to Safe HRI

Category	Identified Needs
Infratechnologies	Supporting standards development (cross-cutting) Taxonomy and paradigms for HRI Risk assessment and measurement tools Testbeds, test protocols, and test procedures Guidelines and best practices
Technology platforms	Sensing and perception for HRI Simulation for HRI
Other	Coordination with other organizations Outreach

Note: Some interviewees provided multidimensional recommendations that were placed under more than one category.

RTI found, based on evidence from interviews, that the cost of integration, specifically the uncertainty over costs, could act as a barrier to adoption for many SMEs, thus creating the need for infratechnology. Standardized risk assessment tools could help drive down these costs. One developer's view supports the issue of scalability and integration costs that could hinder the application of safe HRI: "We want collaborative robots to scale in the same way [traditional robots] scaled in the automotive industry. [Collaborative robots] cannot only be deployed by skilled engineers, cannot have safety companies come in for every deployment. No one knows the costs. Companies are not all carefully doing the risk assessment. The new technical specification that is getting formulized right now, my assessment is that a $30,000 to $40,000 robot with proper risk assessment rather than an ad hoc assessment would easily cost three to four times the initial cost."

Also, as an automotive manufacturer pointed out, risk assessment tools, specifically standard test protocols for sensing forces, could be relevant to company testbeds.

5.3.2 Taxonomies and Paradigms for Human-Robot Interaction

Given that collaborative robotics is a relatively new concept, there is a steep learning curve for anyone who is beginning to learn about it. Potential end users are still figuring out what collaborative robotics means and how it can benefit their business. Although industry and government are working on educating individuals and developing common taxonomies and definitions, collaborative robotics needs to be "right-sized," as one developer mentioned, for appropriate situations. Firms with little to no exposure to robotics require assistance in understanding when collaborative robots would be advantageous or when traditional industrial robotics might be more appropriate. One developer pointed out that if an end user is performing high-speed operations, it may be appropriate to install a safety cage and use traditional industrial robots. NIST could document which classes of tasks (and associated ways of measuring these tasks) would be more suited for traditional industrial robots or collaborative robots.

Another interviewee pointed out that paradigms for HRI need to be more realistic, alluding to the fact that paradigms that are being communicated are not as pragmatic as they should be. Best practices and guidelines would be valuable for industry as it considers implementing collaborative robots and safe HRI. An integrator summed up the need: "Guidelines, best practices, and more concrete implementation information around the [safety] standards would be extremely helpful for industry. It would help us move more quickly."

5.3.3 Coordination with Other Groups Such as the Robotic Industries Association

Several interviewees emphasized NIST as a credible, objective, unbiased third party. In relation to the process of setting and promulgating safety standards, a developer of collaborative robots remarked, "NIST is good at putting different players together. This could be a good place for NIST to establish some common expected behaviors. Leave it open to industry on how to communicate, but NIST can help with what to communicate."

Several interviewees involved or familiar with the RIA safety standards process noted that NIST is involved in that process. However, it was noted that additional resources to support NIST's efforts could be beneficial.

5.3.4 Other Potential Roles

A few interviewees suggested that safe HRI can be more rapidly applied and adopted if NIST were working on other technical capabilities such as sensing and perception and/or simulation capabilities. For example, one observer thought that offline simulation to model safe HRI would be beneficial for end users.

6

Sensing and Perception for Unstructured Environments

Sensing and perception for unstructured environments is one of the most important capabilities because it would allow robots to navigate unstructured and/or semi-structured environments, which would enable new applications and more flexible deployment of robots in the factory environment. Improved sensing and perception would also directly support safe HRI.

The development and adoption of sensing and perception technology are inhibited by several barriers to innovation (sources of market failure) such as the difficulty in bringing component technologies together, the scope of commercial applications being broader than the market strategy of any one firm, and the long and uncertain lag between R&D investments and returns.

There appears to be a potential role for the public sector, perhaps through NIST, to play a role in enhancing infratechnologies by conducting research on new sensing technologies, improving interoperability in support of sensing and perception, working on market demonstration efforts. RTI also offers the idea of closer coordination and collaboration with other organizations as a vehicle for lessening innovation barriers, based on many comments from interviewees.

6.1 BARRIERS TO INNOVATION AND SOURCES OF MARKET FAILURE

The barriers to innovation most relevant for sensing and perception are

- difficulties in bringing together component technologies from different industry segments,
- the long and uncertain lag between R&D investments and returns, and
- a scope of commercial applications broader than the market strategy of any one firm.

Sensing and monitoring capabilities that are needed will require advanced systems that tie together optic and tactile sensors with algorithms and robot controllers. Some approaches to sensing and monitoring require large amounts of computing power and thus will need to connect with the cloud-based computing networks. Bringing together these component technologies is difficult because of a general lack of interoperability.

Some approaches to sensing and perception will likely require years of technology development with no guarantee that this particular technology will gain widespread adoption. These long and uncertain lags between R&D investments and financial returns are a barrier to innovation. Approaches to sensing and perception that have shorter development horizons are likely to receive the most attention by developers in the private sector.

Additionally, as is true of many of the capabilities listed in Table 3-2, the scope of commercial applications for sensing and perception technologies is arguably greater than the market strategy of any particular firm, which leads to an underinvestment of private R&D.

Together, these barriers serve to inhibit the development and adoption of sensing and perception technologies that enable greater robot autonomy in unstructured and semi-structured environments.

6.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

Sixty-eight percent of interviewees gave sensing and perception an importance score of 4 or 5, which was the next highest percentage behind safe HRI. There were no notable differences in the average importance scores based on position in the value chain, which indicates broad agreement that this is a technical area worth NIST's attention. The specific needs in this area are much more dispersed, yet common themes emerge (see Table 6-1). More than one-third of interviewees identified at least one need where NIST might be able to play a role in this area.

6.2.1 New Technologies for Sensing and Perception

In several technical areas, interviewees suggested a potential role for NIST in supporting the development of new and improved technologies. Improved robot mobility, navigation methods, machine vision methods, and methods for object identification were all mentioned as areas requiring additional attention. Although technology development per se is generally outside NIST's mission scope, NIST could help develop and enable infratechnologies in these areas.

Table 6-1. Technology Infrastructure Needs Related to Sensing and Perception for Unstructured (or Less-Structured) Environments

Category	Identified Needs
Infratechnologies	Supporting standards development (cross-cutting) Measuring system performance Interoperability Reference dataset Sensor registration and calibration Testbeds
Technology platforms	New technologies for sensing and perception Improved robot mobility Improved navigation methods Machine vision methods Methods for object identification Tactile sensing and perception
Other	Market demonstration Collaboration with other organizations

Note: Some interviewees provided multidimensional recommendations that were placed under more than one category.

An observer from the venture capital industry pointed out that NIST or other public sector entities could participate in navigation research, both the navigation algorithms and how robot arms can be combined with mobile platforms. Companies such as Adept Technology have navigation and obstacle avoidance capabilities, but according to the interviewee, these capabilities are somewhat rudimentary.

It was also suggested that the robots need to be able to distinguish objects from one another. A particularly interesting approach to object recognition described by a collaborative robotics manufacturer involved very little sophisticated machine vision at all. The idea involved having large cloud-based libraries of objects that correspond to object tags or barcodes. All a robot needs to do is scan the tag or barcode, or become aware of the object’s unique identifier through wireless sensing so that the robot knows what the object is and all of its associated features.

It also appears that there is demand for sensors that can operate in extreme environments subject to temperature changes, high pressure, high speeds, or difficult surfaces. For example, a machine vision expert mentioned a need for auto-focusing optical methods that can handle objects moving at high speeds by focusing in milliseconds and that are robust to rapid temperature changes. These types of auto-focusing methods would be useful generally for high-volume inspections.

In terms of the tactile end of the sensing and perception spectrum, there may be a role for NIST to undertake R&D related to dexterity, although one interviewee pointed out that this may be more of a long-term research project. A manufacturer of end effectors stated that although sensor registration and automated calibration procedures are state of the art, NIST’s research on performance-benchmarking tools and metrics will help manufacturers assess whether a given robot has the requisite fine motor skills needed for certain tasks in a factory (NIST, 2015). However, not all interviewees agreed. Another interviewee emphasized that performance-benchmarking tools for dexterity may be useful in the long term, but in the short term, NIST could work more closely with industry partners to identify more immediate needs for sensing and perception performance benchmarking.

Interoperability

Several interviewees drew a direct connection between improved interoperability and improved sensing and perception. It was noted that improved interoperability will increase innovation in sensing and perception because the commercial incentives will be greater. Furthermore, the lack of interoperability increases the labor costs associated with implementing enhanced sensing and perception. One interviewee described this need as "Standardized software drivers and communications protocols would be something NIST could help with. Most of the costs are labor hours. [Examples are] standards for USB and EB9 connectors." See Section 8 for additional details about interoperability needs.

Market Demonstration

NIST has a role to play in demonstrating the application of new sensing and perception technologies. A developer noted that there is no "big picture approach of how robots would work with people." Another integrator/user of robotics said that NIST could put implementation strategies in the public domain. A major roadblock to market demonstration is finding willing collaborators in the private sector. Companies may be hesitant to do this because they risk the loss of intellectual property. Perhaps NIST can find market demonstration mechanisms that diminish the risks and hesitations on the part of companies while providing some relevant information to other manufacturers.

Collaboration with Other Organizations

Interviewees reiterated the need for NIST to work closely with industry associations such as the RIA and other organizations to alleviate barriers to innovation. However, specific means of collaboration were not spelled out.

Other Potential Roles

A large automotive manufacturer familiar with NIST suggested that NIST become involved in developing standards around measuring systems performance of vision-guided robotic systems. Another developer pointed out that measuring and understanding performance at a granular product level are currently well understood, but they fall apart at the systems level: "Validating sensors, calibration, performance benchmarks on an individual product level is easy, but as soon as it becomes part of a system, how it functions, how data is utilized, becomes difficult to program and tie together."

Yet, even at the individual product level, there are still apparent needs. Sensor registration and calibration, including self-calibration, were mentioned by a metal product manufacturer who made products with very small tolerances.

Interviewees also identified other roles for NIST such as providing testbeds, generating reference datasets, and contributing to standardization. In relation to some of the other technical areas, several interviewees pointed out that sensing and perception on the whole is more of a long-term research topic for NIST than one that will have immediate payoffs. One specific long-term research topic that was mentioned is knowledge representation and reasoning (KR&R). One R&D expert from the automotive industry stated that "KR&R is more academic" in nature. Although some aspects of KR&R can have a more immediate impact, industry appears to view it as a more long-term research topic.

7 Intuitive Interfaces

Intuitive interfaces for interacting with robots is an important industry need, especially considering the lack of skilled workers and technical knowledge that many companies described as a barrier to adoption.

Intuitive methods of programming and teaching robots such as GUIs would make robots more accessible to all manufacturers, specifically SMEs, which tend to have a smaller pool of technical knowledge to tap into.

The development and adoption of intuitive interfaces is inhibited by several barriers to innovation (sources of market failure) such as the risk that R&D outcomes, while technically sufficient, will gain insufficient market acceptance and difficulties in bringing together component technologies.

NIST can accelerate the development and adoption of intuitive interfaces by playing a direct role in their development. Comparisons were drawn between the need for intuitive robot interfaces and other languages such as SQL and M-code.[49] These comparisons may indicate that although a GUI would be beneficial, the most important aspect of intuitive interfaces may simply be standardizing robot programming across the industry. This would prevent individuals from having to learn multiple robot programming languages and would allow a set of work instructions to be executed by any robot regardless of supplier.

Other industry initiatives toward this end, such as ROS and ROS-I, are under way. It is important that NIST research

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[49] M-code is a subset of machine functions in G-code, a commonly used numerical control programming language.

activities dovetail and complement existing efforts. NIST is working with this effort and is using ROS-I in ongoing projects.

7.1 BARRIERS TO INNOVATION AND SOURCES OF MARKET FAILURE

The barriers inhibiting the development and adoption of intuitive interfaces are

- commercial or market risk—the risk that R&D outcomes, although technically sufficient, will not be received well by the market, thereby providing an unacceptable return on investment; and
- difficulties in bringing together component technologies (i.e., interoperability).

Market risk, brought about by market structure, may be the greatest barrier inhibiting the development and adoption of intuitive interfaces. Although there appears to be demand for intuitive interfaces by end users, major robot suppliers may prefer to maintain the status quo for robot programming—each robot supplier having its own proprietary robot programming language—because it limits customers' ability to easily switch to other vendors. As systems become more standardized, robot suppliers may fear the loss of customer and other competitive advantages.

Although some major robot suppliers appear to be moving toward more open robot systems, developers of intuitive robot interfaces may produce a technology that does not gain traction with robot suppliers. This market risk inhibits investment in R&D.

Difficulties bringing together component technologies are another barrier for developing intuitive interfaces. There is a plethora of traditional industrial robots and collaborative robot suppliers. Being able to develop an intuitive robot interface that works across all robots requires an in-depth understanding of all of these products and developing translators that can communicate between the intuitive interfaces and each of the proprietary systems. One interviewee suggested that the programmable logic controllers (PLCs) may be part of the solution to this problem.

7.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

Sixty-five percent of interviewees gave intuitive interfaces an importance score of 4 or 5. End users attributed a much higher importance score to intuitive interfaces than developers. In fact, end users rated intuitive interfaces the most important of the six technical areas. Although end users generally placed a high importance on intuitive interfaces, the specific needs in this area are much more dispersed, and only 20% of all interviewees provided a specific potential role for NIST, indicating that there may be a lack of clarity around what the appropriate role for NIST would be to complement existing industrial activities (see Table 7-1).

7.2.1 Standardized Robot Programming

Several interviewees noted that the lack of ease of use of robots can be a barrier to adoption—specifically, the ability to re-task and re-train robots as needed rather than installing a robot for a particular task for a set number of years, as has been the case in the automotive sector. Other studies have noted user friendliness as a barrier to adoption as well (PricewaterhouseCoopers, 2014). Companies such as Rethink Robotics and Universal Robots have made efforts to simplify the user experience with their robots that are branded as collaborative.

Table 7-1. Technology Infrastructure Needs Related to Intuitive Interfaces

Category	Identified Needs
Infratechnologies	Technology specifications Assess software systems design Interoperability with equipment Standard libraries and methodologies
Technology platforms	Mobility, monitor robot status on a device Standardized robot programming

Note: Some interviewees provided multidimensional recommendations that were placed under more than one category.

To enable more flexible uses of robotics for factories with a more diverse product mix, several interviewees noted that NIST could contribute to developing a more standardized, generic programming interface. One aerospace manufacturer stated that “because it links with sensing and perception, ROS helps but much up front work is still needed.”

An electronics manufacturer stated that a simple GUI would be ideal.

An automotive R&D expert suggested that a standard programming interface would need to be able to communicate with each robot controller by understanding the internal programming and protocols to perform the necessary conversion. A developer drew a comparison between a standardized methodology for programming robots and M-code, a machine tool standard that generalizes work instructions for computer numerical control systems and other machines.

7.2.2 Other Potential Roles

A few interviewees pointed out other infratechnology needs including developing standard libraries to support existing robot interfaces, assessing robot software systems design, and contributing to infratechnologies that support monitoring the status of a robot via mobile device.

8 Interoperability and Modularity

Interoperability and modularity, although not the most important capability in and of itself, can support other capabilities such as sensing and perception and intuitive interfaces. Improved interoperability and modularity of robotics technology alleviates the difficulty of bringing together component technologies, which is a common barrier to innovation in this industry.

Plug-and-play interoperability can be achieved by standardizing physical interfaces, electronic interfaces, and software interfaces, or translators.

Interoperability and modularity is inhibited by several barriers to innovation (sources of market failure) such as positive network externalities, difficulties in bringing together component technologies such as physical interfaces for hardware or communications protocols for software, and industry structure.

NIST can accelerate the development and adoption of intuitive interfaces by conducting research that supports standardization. NIST can also emphasize the importance of coordination among robot manufacturers, end users, industry associations, and professional groups. Horizontal interoperability and vertical interoperability are needed.

8.1 BARRIERS TO INNOVATION AND SOURCES OF MARKET FAILURE

The inability to appropriate all social benefits, such as positive network externalities, is the main barrier that inhibits the development of more interoperable and modular robotics technology. Improved interoperability and modularity of robotics technology would alleviate the difficulty of bringing together component technologies, which is a common barrier to innovation that spans the needed capabilities (see Sections 5.1, 6.1, and 7.1). These broad-based benefits are difficult for any single firm to appropriate.

8.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

Fifty-eight percent of interviewees assigned interoperability and modularity an importance score of 4 or 5, which was the fourth highest percentage compared to all of the capabilities listed in Table 3-2.[50] The average scores for developers and end users were almost identical. Of all interviewees, 32% provided a specific potential role for NIST. Most comments centered on interoperability with robot components and peripherals, interoperability with other systems and machines, coordinating with other organizations, and enabling interoperability through standards (see Table 8-1).

8.2.1 Interoperability with Components and Peripherals (Horizontal Interoperability)

The infratechnology needs voiced by interviewees for interoperability with components and peripherals include end effectors, tooling, robot arms, vision systems, and safety systems. Those needs mentioned ranged from communication standards, physical connection and interface standards, and operating system standards.

One industrial automation developer said efforts have been made in these areas, but he had “doubt that anything has crossed [robot] platforms.” A collaborative robot developer said industry-wide standards would help the industry grow more rapidly because proprietary standards and custom, integrated solutions have actually constrained the industry’s ability to expand. Overall, the industry appears to be a long way from plug-and-play interoperability. One developer said he wanted “physical interfaces and physical behavior defined. If you can specify an interface between a robot and a safety monitoring system, you reduce the need for engineering degrees.”

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[50] See Figure 3-5 for a comparison of scores.

Table 8-1. Technology Infrastructure Needs Related to Interoperability and Modularity

Category	Identified Needs
Infratechnologies	Interoperability with components, peripherals Interoperability with other systems Standards development Integration with programming
Technology platforms	Characterize factory environments
Other	Adoption of standards

Note: Some interviewees provided multidimensional recommendations that were placed under more than one category.

8.2.2 Interoperability with Other Systems (Vertical Interoperability)

Plug-and-play interoperability allows end users to choose their preferred robot components, software, and vision systems. Plug-and-play interoperability enables the robotic system to “talk” with other factory systems and machines, which would entail additional benefits.

Manufacturing enterprise solutions vary from plant to plant and company to company. One developer suggested that NIST could help define standards for warehouse systems, specifically standards for instructions to robots on when to execute a task or subset of tasks. NIST could help define standards for communications back to the manufacturing execution system regarding what has been completed, cycle times, performance metrics, and other granular data. Part of the interoperability challenge is clarity around protocols for combining wired and wireless communications in ways that do not compromise security.

8.2.3 Standards

Although many interviewees believe that standards are needed, part of the challenge may be coordinating and persuading big players to adopt existing standards. One machine vision developer pointed out that a barrier to interoperability is not the lack of standards and protocols, but rather the lack of adoption of the standards and protocols by the big players in robotics manufacturing. One interviewee suggested a possible role for NIST or other public sector bodies to facilitate coordination among robot manufacturers, end users, industry associations such as Semiconductor Equipment and Materials International, and professional groups such as IEEE.

9 Modeling and Simulation

Modeling and simulation appeared to be somewhat less important relative to some of the other capabilities. However, modeling and simulation tools for risk assessments could enable the more efficient deployment of collaborative robots.

Simulation could significantly reduce the time and cost involved in changing between production lines if the factory floor was software reconfigurable. Other benefits of simulation include a better understanding of tool paths and documenting as-built products compared with their digital counterparts. Simulation models could also be used to convert robot training and teaching on the factory floor into transferable knowledge that can be applied to different situations in the future.

Modeling and simulation is inhibited by two barriers to innovation (sources of market failure): technical risk and the difficulty of bringing together component technologies.

The most important future application of simulation appears to be for supporting safe HRI through risk assessment and quantification of relevant dimensions of HRI. Key infratechnologies that NIST can provide include libraries, reference data, and reference models. There are also some industry needs around measuring the fidelity of simulation models.

9.1 BARRIERS TO INNOVATION AND SOURCES OF MARKET FAILURE

Technical risk and difficulties in bringing together component technologies act as barriers to innovation that inhibit the development of modeling and simulation technology. With advanced simulation models, there is a risk that R&D will yield insufficient technical outcomes. It is extremely challenging to develop a simulation model that adequately captures the role that robots play in a variety of manufacturing industries with widely different production processes. Furthermore, different levels of fidelity are needed for different situations, and a one-size-fits-all approach to simulation may not suffice.

As with the other capabilities, the lack of interoperability of component technologies makes simulation more difficult because it is not simple to model a digital expectation of how a patchwork of component technologies will work together as a system.

9.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

Forty percent of interviewees gave modeling and simulation an importance score of 4 or 5. Users attributed slightly more importance to modeling and simulation than developers. Only 23% of all interviewees provided potential roles for how NIST can contribute in this area (see Table 9-1).

The most important future application of simulation appears to be for supporting safe HRI through risk assessment and quantification. Key infratechnologies for simulation include libraries, reference data, and reference models. Another measurement issue is the level of fidelity achieved when combining different robots with different simulation systems.

Finally, a longer-term research topic would be how to use simulation for virtual testing of machine vision systems. Another noteworthy idea was creating a computer-aided design import-robot output tool similar to the instructions that are used for CNC machines.

It is important to note that although modeling and simulation capabilities are somewhat less important for robotics, they are highly relevant for smart manufacturing as discussed in one of the companion report to this one titled *Economic Analysis of Technology Infrastructure Needs for Advanced Manufacturing: Smart Manufacturing Processes*.

Table 9-1. Technology Infrastructure Needs Related to Modeling and Simulation

Category	Identified Needs
Infratechnologies	Data for simulation, libraries Machine vision, virtual testing Measure for fidelity of robot-simulation combination Reference models
Technology platforms	Computer-aided design import tool, robot output tool Simulation for safe HRI

Note: Some interviewees provided multidimensional recommendations that were placed under more than one category.

10 Objective, Low-Cost Performance Characterization

Objective, low-cost performance characterization would address informational asymmetries between developers and end users of robots. The importance of this capability depends on the unique context and situations of each end user.

If objective, low-cost performance characterization were to be standardized, it could stimulate innovation by giving users a common way to communicate needs to developers and by giving developers a common target for focusing R&D efforts. However, interviewees suggested that the role for NIST might be limited here because industry would need to lead any measurement standards. Generally, industry has to be involved in developing standards that it will use, but the importance of industry involvement is particularly strong in this case because performance measures are directly used to market robotics technologies.

Perhaps the single greatest need for performance characterization would be in the area of measurement supporting safe HRI.

10.1 BARRIERS TO INNOVATION AND SOURCES OF MARKET FAILURE

Several barriers have limited objective, low-cost performance characterization, but the most prominent is informational asymmetries between developers and end users of robotics technology. Objective, low-cost performance characterization would help address these informational asymmetries.

Objective data would benefit end users and developers by lessening transaction costs involved in overcoming common informational asymmetries. In the absence of such data, end users find it costly to convey their needs to developers, and developers similarly find it costly to communicate to the end users what their systems can and cannot do and to prove that their systems will perform as advertised. Furthermore, there may be situations where end users do not realize that they are paying for capabilities that are not optimal for their particular applications. As one developer of robot end effectors noted, “We’ve come across smaller customers where they need to buy a robot for a particular task, [and] they are sometimes misled into buying 6 axis robots, but they only need a faster 2 axis robot. Being able to have standard ways of communicating that would be important for our customers.”

Common metrics for evaluating robotic systems are not only important for end users of robots, but common metrics can also give robot developers a common target for focusing R&D efforts, which could serve to stimulate innovation.

10.2 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

Developers and end users agreed that this capability was the least important of the six that we outlined in our interview guide. Only 30% of interviewees gave this an importance of 4 or 5. It appears that objective, low-cost performance characterization would be something nice to have, but other capabilities are more clearly more pressing. Many interviewees did not perceive this to be an issue at all.

A few individuals were outspoken regarding their belief that this is an important issue. A machine vision developer (and others) suggested that robot vendors are not transparent in how they measure repeatability. One developer went as far as to say that if performance characterization is done right, it will stimulate innovation.

Others gave a more nuanced explanation, explaining that performance characterization is relevant to only the very sophisticated end users. A robotics gripper manufacturer stated, “Performance characterization is important to upper echelon of manufacturing—automotive and others that run 3 shifts a day.”

There are examples of where technology developers can improve performance characterization and make it more transparent, but most people believe that current market conditions are sufficient and any standardization in how developers define and measure performance of their products—ultimately, how developers market their products to customers—would need to be industry driven. Perhaps the single greatest area of performance characterization would be in the area of measurement supporting safe HRI (see Section 5).

11 Conclusion

The deployment of robots in the U.S. manufacturing sector has largely been limited to automotive manufacturing. If critical enabling infratechnologies were in place, advanced capabilities, such as safe HRI and enhanced sensing and perception, would be possible. The existence of advanced capabilities (and associated infratechnologies), as outlined in this report, would stimulate industry investment in robotics technology and lead to the realization of an estimated $40.4 billion in net economic savings of U.S. manufacturers.[51]

As robots become more user friendly and easier to integrate with existing production lines, SMEs, which have limited adoption of robotics, would be able to implement robotics and automation technologies on a broader scale. Increased adoption of robots in the U.S. manufacturing sector would reduce labor costs, increase productivity, and improve product quality. These economic impacts would support the policy goal of improving the international competitiveness of the U.S. manufacturing sector.

Several barriers to innovation lead to a shortage of critical infratechnologies and inhibit the development and adoption of robotics technology. The rate and extent of development of robotics technologies with the needed capabilities and the rate and extent of their adoption in advanced manufacturing applications will depend on the parallel development and diffusion of technology infrastructures that are generally underprovided by the market. This resulting market failure—the failure of the market to allocate a socially optimal level of

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[51] We believe this to be a conservative estimate of net economic savings for the variety of reasons detailed in Section 2.

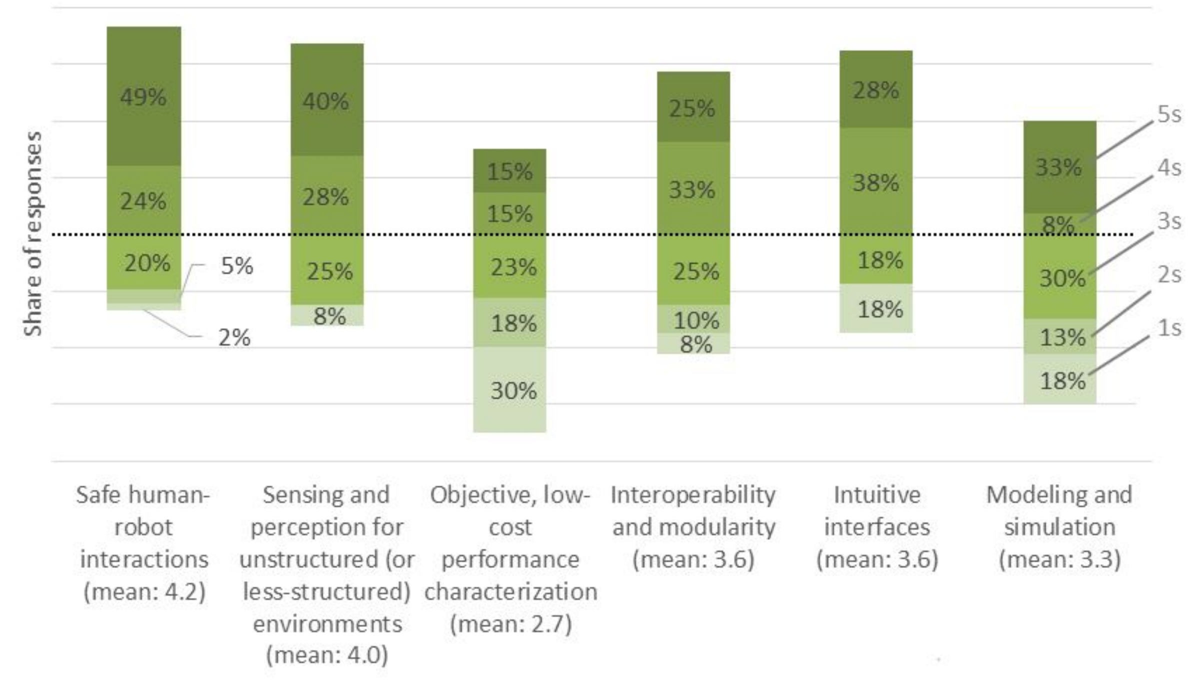
infrastructure—provides an opportunity to improve the efficiency of economic outcomes through public investments in technology infrastructure. NIST can accelerate the realization of the economic benefits of robotics technology by providing and contributing to infratechnology. Industry experts throughout the robotics and automation fields have recommended a variety of roles for NIST to support capabilities by providing infratechnologies.

11.1 CAPABILITIES AND INFRATECHNOLOGY NEEDS

Interviewees indicated the importance of a broad range of capabilities for robotics and automation (see Figure 11-1).

If we interpret important as a 4 or a 5 and not important as a 1, 2, or 3, the most important capabilities ranged from safe HRI; to sensing and perception for unstructured or semi-structured environments; to interoperability and modularity of robots with components, peripheral devices, and other systems; and to intuitive interfaces for robot programming.

Figure 11-1. Importance of Capabilities/Needs and Corresponding Infratechnology Needs, Diverging Stacked Bar Chart



In addition to the implicit hierarchy of importance illustrated in Figure 11-1, there are significant interdependencies between the capabilities. For example, although objective, low-cost performance characterization received the lowest average importance score, technology infrastructure that supports objective, low-cost performance characterization can make it more feasible to implement safe HRI. Additionally, modeling and simulation tools can support safe HRI. Furthermore, improved interoperability and modularity could stimulate innovation in sensing and perception by broadening the potential market size for new sensing technologies.

Notwithstanding these interdependences, the level of importance of these capabilities might be viewed as a second-order indicator for the areas in which NIST could play a role in advancing the development and adoption of robotics technology by providing infratechnologies.

11.2 ECONOMIC IMPACTS

Interviewees were asked about the economic impact that enhanced robotics and automation capabilities and associated infratechnologies could have on their manufacturing processes. Table 11-1 shows the average percentage change in KLEM factor inputs provided from the interviews.

End users indicated that labor costs could be reduced by an average of 18%, and materials costs could be reduced by 8%. These cost savings could be achieved by a net increase in capital expenditures of 22%. The economic impact of the increased adoption of robotics and automation on energy consumption would be negligible.

Changes in factor inputs were then scaled to the national level to estimate the economic impacts associated with enhanced infratechnology. Table 11-2 shows that national economic impacts are estimated to be approximately $40.4 billion.

Table 11-1. Percentage Change in Factor Inputs Due to Meeting Industry Needs

Factor Input	Mean Impact of Meeting Industry Needs
K: Capital	+22%
L: Labor	−18%
E: Energy	+1%
M: Materials	−8%

Table 11-2. Economic Impact Summary Table

	Industry Data, 2013		Cost Impacts, Billions					
	Sales	Shop Floor KLEM National Factor Expenditure	K: Capital	L: Labor	E: Energy	M: Materials	Total	Percentage Impact
Total	$2.13 trillion	$759 billion	+$11.4	−$22.1	−$0.4	−$29.3	−$40.4	−5.3%

Note: Industry detail is provided in Table 4-3.

The aggregate national economic impacts represent, on average, a 5% reduction in national factor expenditures. Materials savings, although a smaller percentage impact than labor savings, accounts for the largest share of savings because it accounts for approximately three-fifths of manufacturing production costs.

11.3 TECHNOLOGY INFRASTRUCTURE NEEDS AND POTENTIAL ROLES FOR NIST

Industry experts provided specific recommendations regarding the role NIST could play to accelerate the development and adoption of robotics technology in the U.S. manufacturing sector. Interviewee recommendations provide a first-order indicator of where NIST could lead, coordinate, or encourage development in each of these areas. An overview of some of the most commonly cited recommended roles for NIST is provided below.

11.3.1 Risk Assessment and Measurement Tools for Safe Human-Robot Interaction

Although the RIA and ISO have promulgated safety standards and recent technical guidance, the interviewees with whom we spoke think that additional work can be done on safety standards to empower manufacturers to apply them. Interviewees stated that it is difficult to implement the standards even with the added benefit of injury data in the new ISO technical specification document. Interviewees suggested that NIST can contribute significantly to the continued development of safety standards and practices by developing and standardizing metrics and test protocols for measuring robot safety outside of a cage. For example, standardized metrics are needed for measuring pain, force, torque, and risk. Some work is being done in this area already, but NIST can contribute.

As a suite of metrics and test protocols starts to form, NIST can provide streamlined tools for risk assessment in collaborative robot applications involving safe HRI. Risk assessment and measurement tools could accelerate the adoption of robots by making robots less costly to integrate with existing production lines.

11.3.2 New Technologies for Sensing and Perception

Improved robot mobility, navigation methods, machine vision methods, dexterity, and methods for object identification were all mentioned as areas that require additional attention. There also appears to be demand for sensors that can operate in extreme environments subject to temperature changes, high pressure, high speeds, or difficult surfaces.

Some of the needs for new sensing and perception technologies will likely have long-term horizons before research can be applied in the manufacturing sector.

A more near-term research activity for NIST to support object identification described by a collaborative robotics manufacturer involved NIST providing large cloud-based libraries of objects that correspond to object tags or barcodes, which can a robot can wirelessly sense or optically scan in order to recognize all of the object’s associated features.

11.3.3 Standardized, More Intuitive Robot Programming

The lack of ease of use of robots can be a barrier to adoption—specifically, the ability to re-task and re-train robots as needed rather than installing a robot for a particular task for a set number of years, as has been the case in the automotive sector.

To enable more flexible uses of robotics for factories with a more diverse product mix, several interviewees noted that NIST could contribute to developing a more standardized, generic programming interface or GUI.

Comparisons were made to SQL and M-code. Any activities that NIST undertakes in this area will need to complement existing industry activities such as ROS and ROS-I.

11.3.4 Interoperability

Improved horizontal interoperability—interoperability with components and peripherals including end effectors, tooling, robot arms, vision systems, and safety systems—and vertical interoperability—would serve to stimulate innovation and decrease the costs of installing and integrating robotics technology. Improved interoperability requires software, electronic, and physical hardware connection and interface standards.

Plug-and-play interoperability enables end users to choose their preferred robot components, software, and vision systems. Plug-and-play interoperability also enables the robotic system to “talk” with other factory systems and machines, which would entail additional benefits.

Additionally, there is a direct connection between improved interoperability and improved sensing and perception. Improved interoperability will increase innovation in sensing and perception because the commercial incentives will be greater. Furthermore, the lack of interoperability increases the labor costs associated with implementing enhanced sensing and perception.

11.3.5 Coordination with Other Organizations

NIST is a credible, objective, unbiased third party that can provide inputs to the standard setting process. However, additional resources to support NIST’s efforts could be beneficial. There is a need for NIST to work more closely with industry groups and companies across a variety of technical areas to alleviate barriers to innovation.

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Appendix A: Interview Guide for Robotics/Automation Systems Developers

NIST Advanced Manufacturing Strategic Planning Study Interview Guide for Robotics/Automation Systems Developers

The National Institute of Standards and Technology (NIST) in the U.S. Department of Commerce has contracted with RTI International to conduct an economic analysis of standards, measurement, and general purpose technology needs that inhibit efficient development and adoption of advanced manufacturing in the United States.

The objectives of this critical strategic planning study are to

- identify current and emerging needs related to standards and measurement,
- estimate the economic impact of meeting these needs, and
- review public policy and investment options.

The study has a particular focus on 4 aspects of advanced manufacturing: (1) robotics and automation, (2) smart manufacturing processes, (3) 3D Printing (additive manufacturing), and (4) roll-to-roll manufacturing. The focus of our conversation is robotics and automation.

Your perspective will help guide NIST's planning and investment process. Participation in this analysis is confidential; only aggregated information will be included in any deliverables or communications. Your name and your company's name will not be disclosed. We do not wish to discuss specific products, strategies, or technologies; but rather your thoughts about how investments in standards and measurement technologies would affect your company and companies like yours.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in late 2015 and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Alan O'Connor, Principal Investigator, RTI, 919-541-8841 or oconnor@rti.org
- Gary Anderson, NIST Project Officer, NIST, 301-975-5238 or gary.anderson@nist.gov

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Table A-1. Respondent Contact Information

Name	
Title	
Company	
Industry	
Phone	
Email	
Location	

Respondent Background

1. Please give a brief description of your experience with robotics and automation systems.

About Your Company

2. What types of robotics and automation systems does your company develop?

3. What are your customers' primary lines of business (i.e., industry classification)? In other words, what are the manufacturing applications in which your systems are most commonly used?

Industry Needs

Several industry-level needs have been identified, and discussions with experts have suggested measurement and test methods, material and process standards, reference databases, and general purpose technologies that could meet these needs.

Please review the summary table on the next page, thinking about how these needs apply to your company's development of robotics and automation technology.

Table A-2. General Industry-Level Needs for Robotics and Automation

Industry Needs	Infrastructure Technology to Help Meet Needs	Rating of Importance (1 to 5) 5=Most 1=Least
Safe human-robot interactions Universal standards for developers of robotic technologies and the application of these technologies in manufacturing settings with robots working in close proximity to people (see more below on sensing/perception for unstructured environments, relevant for intuitive HRI)	• Test protocols, objective scientific and engineering data, reference databases, and other technical inputs into standards for safe HRI (power/force-limiting; speed/separation monitoring; hand-guided operation; safety-rated monitored stop)	
Sensing and perception for unstructured (or less-structured) environments Improved perception (and the ability to plan and re-plan its actions based on what it “sees” and “knows”) giving a robot greater autonomy, lessening its demand that its work environment meets stringent tolerances	• Sensor registration & calibration • Performance characterization (benchmarks, testbeds, and technical inputs to standards to characterize the performance of systems, subsystems, and components) • Sensing/perception engines/architectures • Proof-of-concept robotics applications of KR&R (knowledge representation & reasoning)	
Objective, low-cost performance characterization Making it easier for robotics users to know what they are buying, easier for developers/suppliers to show what their systems do	• Common performance metrics, objective data, testbeds, test methods, and benchmarks to characterize the performance attributes of advanced systems, subsystems, and components	
Interoperability and modularity Plug-and-play for system components, enabled by standards for physical and electronic interfaces, software interfaces/translators	• Objective technical inputs into the standards-setting process: scientific and engineering data, benchmarks, testbeds, objective third-party testing of candidate technologies/configurations	
Intuitive interfaces Enabling rapid programming/training without specialized skills	• Protocols to simplify the programming, training, and rapid re-tasking of robots • Standard programming language for industrial robotics analogous to SQL or HTML	
Modeling and Simulation Virtual factory floor allowing modeling and simulation, calibrated based on real-time data feed from robots, machine tools, sensors, control systems on the floor.	• Robust, open, real-time operating system on the factory floor • Reference models, modeling frameworks to fully integrate robots into models of the manufacturing environment and enable robust simulation/prediction	

4. Are any of the Industry Needs the focus of current R&D at your company? Which ones?
5. If one or more of the infrastructure technologies described were to become (more) available, would it benefit your company? If so, how?
6. Which items (both Needs and Infrastructure Technology) listed in the table are most relevant to your company? If several items are relevant, how would you prioritize them?
7. Are there items not included in the table that you would include? If so, what are they?
8. If the Infrastructure Technology described above was available today, how would that impact your company's development and commercialization of robotics/automation systems?

Table A-3. Development and Commercialization

	Impacts	**Description of Impact**	**+/- % Change, if applicable**
a	R&D costs?		%
b	R&D opportunities (likelihood of technical success)?		%
c	Market opportunities?		%
d	Accelerated development of technologies improving the performance of existing products?		%
e	Accelerated development of altogether new products?		%
f	In other ways?		%

9. Would you expect any changes in your company's investment patterns or risk tolerance, if the Infrastructure Technology described above was available today? If so, what types of changes?
10. Could you briefly describe what could be expected in terms of new products or applications if this infrastructure technology was all available today? Would certain kinds of robots come to market sooner, or would robots be used in new ways sooner?

11. To enable us to combine your responses with the responses of others and provide NIST with a sense of potential impacts at the industry level, could you quantify these impacts in terms of a relative change in your company's sales?

Table A-4. Sales

Sales	%

12. Would you say that your answer to question 11 is representative of your industry (of companies developing/commercializing robotics/automation systems), or of only a subset? Please explain briefly how, if at all, the anticipated impacts for your company may be different from the industry as a whole, or how different industry segments may be differently impacted.
13. Are there any additional comments you would like to share?

Appendix B: Interview Guide for Robotics/Automation Systems Users

NIST Advanced Manufacturing Strategic Planning Study Interview Guide for Robotics/Automation Systems Users

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Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in late 2015 and these will be shared with you as soon as they are released.

If you have questions, please contact:

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- Alan O'Connor, Principal Investigator, RTI, 919-541-8841 or oconnor@rti.org
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Respondent Contact Information

1. Name
2. Title
3. Division
4. Company
5. Telephone
6. Email
7. Location, if not USA

Respondent Background

8. Please give a brief description of your experience with robotics and automation systems. How did you come to be in your current position?
9. How familiar are you with the National Institute of Standards and Technology?

About Your Company

10. How would you describe your primary line of business (i.e., industry classification)? What do you produce and sell most?

  a. Approximately what percentage of your company's sales revenue is associated with your division, or the division for which you are responsible? A range is fine.

11. How does your company use robotics and automation systems?
    a. For what manufacturing processes, or for the manufacture of what products?
    b. What types of robotics and automation systems do you use?
12. As far as you are aware, is your division or company engaged with any industry consortia, standards organizations, or governing bodies specifically for advanced robotics and automation? If so, in which bodies do you participate and what are the underlying drivers for participation?
13. Generally, does your company conduct R&D related to the adoption, adaptation, and/or use of robotics and automation systems? If so, what are the broad objectives of that R&D (e.g., cost reduction, quality improvement, other)?

Industry Needs

Several industry-level needs have been identified, and discussions with experts have suggested measurement and test methods, material and process standards, reference databases, and general purpose technologies that could meet these needs.

Table B-1. General Industry-Level Needs for Robotics and Automation

Industry Needs	Infrastructure Technology to Help Meet Needs
Safe human-robot interactions Universal standards for developers of robotic technologies and the application of these technologies in manufacturing settings with robots working in close proximity to people (see more below on sensing/perception for unstructured environments, relevant for intuitive HRI)	Test protocols, objective scientific and engineering data, reference databases, and other technical inputs into standards for safe HRI (power/force-limiting; speed/separation monitoring; hand-guided operation; safety-rated monitored stop)
Sensing and perception for unstructured (or less-structured) environments Improved perception (and the ability to plan and re-plan its actions based on what it “sees” and “knows”) giving a robot greater autonomy, lessening its demand that its work environment meets stringent tolerances	Sensor registration & calibration Performance characterization (benchmarks, testbeds, and technical inputs to standards to characterize the performance of systems, subsystems, and components) Sensing/perception engines/architectures Proof-of-concept robotics applications of KR&R (knowledge representation & reasoning)
Objective, low-cost performance characterization Making it easier for robotics users to know what they are buying, easier for developers/suppliers to show what their systems do	Common performance metrics, objective data, testbeds, test methods, and benchmarks to characterize the performance attributes of advanced systems, subsystems, and components
Interoperability and modularity Plug-and-play for system components, enabled by standards for physical and electronic interfaces, software interfaces/translators	Objective technical inputs into the standards-setting process: scientific and engineering data, benchmarks, testbeds, objective third-party testing of candidate technologies/configurations
Intuitive interfaces Enabling rapid programming/training without specialized skills	Protocols to simplify the programming, training, and rapid re-tasking of robots Standard programming language for industrial robotics analogous to SQL or HTML
Modeling and Simulation Virtual factory floor allowing modeling and simulation, calibrated based on real-time data feed from robots, machine tools, sensors, control systems on the floor.	Robust, open, real-time operating system on the factory floor Reference models, modeling frameworks to fully integrate robots into models of the manufacturing environment and enable robust simulation/prediction

14. Do any of these needs apply to your company's use of robotics/automation? In other words, if one or more of these needs were to be met, would it benefit your company? If so, how?

15. If several needs were discussed in question 14 as being relevant to your company, could you prioritize them? Which are the most important?

16. Are there needs not included in the table that you would include? If so, what are they?

17. If these needs were all met today, how would that impact your company's R&D and production?

    a. Changes in the types of robotics and automation systems used?
    b. Changes in the range of products for which at least some manufacturing processes/tasks are automated?
    c. Changes in the range of manufacturing processes/tasks that are automated?
    d. Others?

18. Can you describe any types of impacts on your company if these needs were met, in terms of costs of production? A range is fine.

    a. Changes in time needed to configure/test/validate product line or work cell?
       (+ / − by roughly what %? __________%)
    b. Changes in cost to configure/test/validate product line or work cell?
       (+ / − by roughly what %? __________%)
    c, Changes in unplanned downtime, when workers and equipment are idle?
       (+ / − by roughly what %? __________%)
    d. Changes in duration of product-development-to-production cycle?
       (+ / − by roughly what %? __________%)
    e. Others?
       (+ / − by roughly what %? __________%)

19. To enable us to combine your responses with the responses of others and provide NIST with a sense of potential impacts at the industry level, could you quantify the impacts we have discussed in terms of the following metrics? A range is fine.
    a. Cost of materials + / − __________%
    b. Cost of energy/electricity + / − __________%
    c. Cost of labor + / − __________%
    d. Cost of capital equipment + / − __________%
    e. Overall cost of production + / − __________%
20. Would you say that your answer to question 19 is representative of your industry (of companies in similar lines of business), or of only a subset? Please explain briefly how, if at all, the anticipated impacts for your company may be different from the industry as a whole, or how different industry segments may be affected differently.

21. Switching from thinking about costs to thinking about your company’s product offering, could you briefly describe what changes could be expected if these needs were all met today?

    a. Changes in the quality of existing products?
    b. Changes in the amount of customization within existing product lines?
    c. Introduction of new products or product lines?
    d. Others?
22. To enable us to combine your responses with the responses of others and provide NIST with a sense of potential impacts at the industry level, could you quantify these impacts in terms of a relative change in your company’s sales? A range is fine. + / − __________%

23. Would you say that your answer to question 22 is representative of your industry (of companies in similar lines of business), or of only a subset? Please explain briefly how, if at all, the anticipated impacts for your company may be different from the industry as a whole, or how different industry segments may be differently impacted.

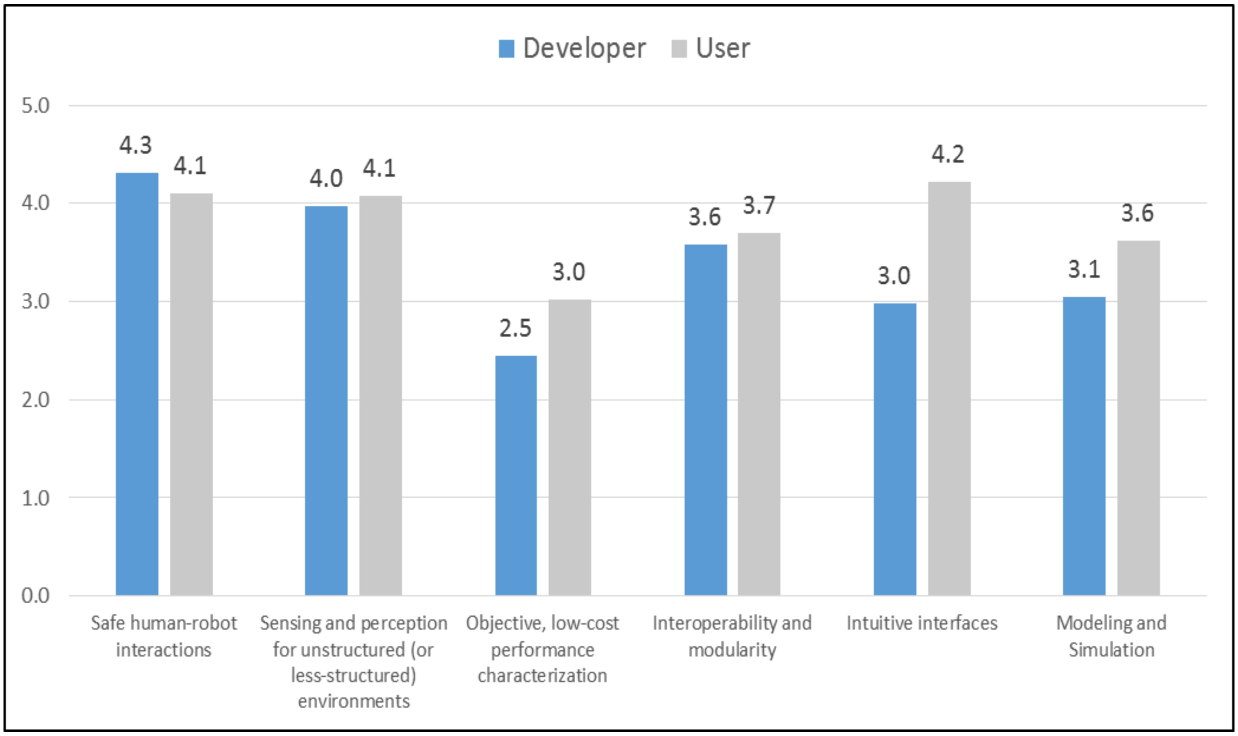
24. Would you expect any changes in your company's investment patterns or risk tolerance, if the types of technologies discussed above were made available? If so, what types of changes?
25. Are there any additional comments you would like to share?

Appendix C: Importance Scores

Table C-1. Rating of Importance of Capabilities/Needs (5=most important, 1=least important)

	Safe Human-Robot Interactions	Sensing and Perception for Unstructured (Or Less-Structured) Environments	Objective, Low-Cost Performance Characterization	Interoperability and Modularity	Intuitive Interfaces	Modeling and Simulation
All Firms						
	4.2	4.0	2.7	3.6	3.6	3.3
Developers						
Mean Score	4.3	4.0	2.5	3.6	3.0	3.1
End Users						
Mean Score	4.1	4.1	3.0	3.7	4.2	3.6

Figure C-1. Rating of Importance of Capabilities/Needs (5=most important, 1=least important)



Appendix D: Vignette

Robotics Has the Potential to Transform Aerospace Product and Parts Manufacturing

Robotics and automation in aerospace manufacturing tend to be used in part fabrication and other tasks that occur early on in the final assembly process. A major aerospace OEM[52] stated that its company uses robotics and automation in workcells that tend to be early in the assembly process, performing tasks such as manipulating composite panel covers, drilling, and fastening. Another OEM described a robot workcell with wiring and circuitry tasks and another workcell for precision welding. A supplier of aircraft fuselages said that his company used robots for painting and drilling.

In general, the adoption of robotics and automation technology in the industry has been limited, particularly to later stages of the assembly process, where OEMs are still employing many manual assembly techniques. When robots are used, they tend to operate in safety cages away from workers.

Looking to the future, the most important capabilities for the industry are safe human-robot interaction (HRI) and sensing and perception for unstructured, or at least semi-structured, environments. Safe HRI is critical because of the labor-intensive nature of later stages of the production process. To truly harness the power of robotics, they must be able to work alongside humans. Sensing and perception will not only support safe HRI, but it would also allow robots to deal with a highly variable production environment where a high variety of parts may be presented to the robot gripper in variable ways.

If the needed capabilities and associated enhanced technology infrastructure are met, this would likely crowd in investment by aerospace OEMs and large component suppliers that could use robots for new applications such as material handling, more dexterous work like riveting, and navigating semi-structured environments to collaborate safely with workers. Investment would be crowded in because the technologies would be less costly to integrate with existing production lines and would yield greater economic benefits compared with current robotics technology.

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[52] OEM, or original equipment manufacturer, is used to describe the manufacturers that assemble and sell the final aircraft.

Industry experts provided context on the particular benefits that enhanced infrastructure technology would have.

Benefit #1: Freeing up Skilled Labor and Improving Quality

Highly skilled technical workers in the aerospace industry are also commonly responsible for later-stage, manual assembly tasks. With enhanced infrastructure technology, it would be possible to safely slot in collaborative robots next to humans. Deploying collaborative robots would free up highly skilled aerospace workers for other less tedious tasks. It could also improve quality, which tends to erode when humans do too much ergonomically taxing, monotonous, or dull work.[53] One industry expert thought that riveting quality would improve with robots because they are more consistent and precise than humans.

Benefit #2: Adding Predictability to the Production Cycle

Increased adoption of robotics technology in the industry could add more predictability to the production cycle. One aerospace manufacturer pointed out that as more manual labor is removed from the production process, one direct result would be less variability in production cycles because of less human error. One OEM described the unpredictable nature of production in terms of non-recurring labor costs that are borne out of rework and last-minute changes when inspections show that a component may have been not installed properly or at all.

Increased predictability is valuable for any manufacturer because it allows them to plan and coordinate supply chain activities more effectively, such as purchasing inputs and delivering to customers on schedule.

Benefit #3: Reducing Work-in-Process Inventory and Reducing Lead Times

Aerospace assembly production cycles last for months and even years. As a side effect of the long production cycles, a tremendous amount of capital is embodied in work-in-process inventories that accumulate as a plane is being built. (These inventories represent a substantial opportunity cost for

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[53] This is true across many industries, not just in aerospace manufacturing and not just in the manufacturing sector.

aerospace manufacturers because it is capital that they cannot invest in other purposes.)

Advanced robotics, which has the potential to speed up throughput and production cycles, could lead to a reduction in work-in-process inventory investments. It will take time for manufacturers to take full advantage of advanced robotics and enhanced technology infrastructure because in some situations, once workcells and production lines are set up, they build the same product for 20 to 30 years. If the impacts from advanced robotics are large enough, that may provide enough of an economic incentive to retrofit or re-plan workcells. Improved production efficiency would add value for customers by reducing lead times for new orders.

Importance of Other Advanced Manufacturing Technologies

Robotics and automation will have a greater effect when they are combined with other advanced manufacturing technologies such as smart manufacturing and additive manufacturing. As one aerospace manufacturer stated, "Robotics is one aspect of a number of things that have the ability to improve the efficiency. Robots and automation alone will not make a massive impact on our business in terms of where they are today."