MANUFACTURING:
Advanced Robotics and Intelligent Automation*

Technology Innovation Program
National Institute of Standards and Technology
Gaithersburg, MD
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The Technology Innovation Program (TIP) at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting United States businesses, institutions of higher education, organizations such as national laboratories, and nonprofit research institutions by supporting, promoting, and accelerating innovation in the United States through high-risk, high-reward research in areas of critical national need.[1]

TIP seeks to enable high-risk, transformative research targeted to address key societal challenges. Funding selections will be merit-based and may be provided to industry (small and medium-sized businesses), universities, and consortia. The primary mechanism for this support is cost-shared cooperative agreements.

AN AREA OF CRITICAL NATIONAL NEED

The proposed TIP funding opportunity in *Advanced Robotics and Intelligent Automation* is a focus within the critical national need area of Manufacturing, although developments also have potential impacts in other areas such as healthcare and homeland security. This topic was selected from a larger set of challenges in manufacturing where transformative research could be expected to have a large societal impact. Input regarding potential challenges in manufacturing was obtained from government agencies, advisory bodies (such as the National Research Council, National Academy of Sciences, and National Academy of Engineering), National Science and Technology Council, Science and Technology Policy Institute (STPI), industrial organizations, leading researchers from academic institutions, and others.

As an area of critical importance to the nation and its economy, the manufacturing sector represents the largest of the United States' private industry sectors and the world's leading producer of manufactured goods. In 2002, the manufacturing sector alone represented the fifth-largest economy when compared to other countries around the world.[2,3] However, by 2007, that ranking had dropped to the equivalent of the eighth largest international economy. Other data for 2007 show manufacturing represented 11.7 percent of the Gross Domestic Product (GDP), supported fourteen million jobs (10.1 percent of U.S. employment), and accounted for more than 90 percent of all U.S. patents registered.[4]

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* According to the IEEE's Robotics and Automation Society,

- *Robotics* focuses on systems incorporating sensors and actuators that operate autonomously or semi-autonomously in cooperation with humans, emphasizing intelligence and adaptability to cope with unstructured environments.
- *Automation* emphasizes efficiency, productivity, quality, and reliability while focusing on systems operating autonomously, often in structured environments over extended periods, and on the explicit structuring of such environments.

The strength and leadership of the manufacturing sector historically has meant that it has been a major contributor in both economic good times and economic recessions. However, the last several recessions have hit manufacturers especially hard. Jobs have been lost due to restructuring, full manufacturing capacity has been slow to return, and new capital equipment orders have been sluggish. Incremental research and development undertaken during such poor economic times, while valuable in the short term, cannot alter the long-term structural challenges faced by the manufacturing sector in these slow economic times. Instead, sustained growth and revitalization of the manufacturing sector requires high-risk, high-reward research – research with the potential to produce transformational results that can change industry opportunities and directions through far-ranging or wide-ranging outcomes. This perspective is supported by organizations such as the National Association of Manufacturers (NAM).[5]

One research area that has the potential to achieve such outcomes is *Advanced Robotics and Intelligent Automation*. For the rest of this discussion, “advanced robotics” will refer to specific design features and capabilities. Specifically, advanced robots are envisioned to be

- Mobile (i.e., no longer bolted to the floor);
- Operate in unstructured, or uncertain, environments (i.e., autonomous);
- Designed to manipulate or physically interact with their environment;
- Capable of achieving desired outcomes without needing a fully pre-programmed precise set of actions for achieving those outcomes; and
- Able to safely perform tasks in intimate operation with humans or in extremely hazardous environments.

Intelligent automation could then build upon the new capabilities of these advanced robots to achieve increased levels of autonomy and flexibility that in turn would enable manufacturers to respond to changes in a more efficient and cost-effective way. However, while the industrial robotics industry has been around since the 1960’s, the advanced robotics industry is still in its infancy and will have trouble developing these highly desirable capabilities on its own. Support is needed that fosters collaboration and integrated, cross-disciplinary solutions if developments are to be achieved in a focused and timely manner.

The next generation of *Advanced Robotics and Intelligent Automation* systems would make possible new levels of speed, accuracy, precision, flexibility and agility, which in turn should provide manufacturers with greater competitiveness, profitability, and high quality employment opportunities. This paper will explore the rationale for why these advances are needed, and suggest opportunities for high-risk, high-reward technology development that could deliver the broader and more far-ranging uses of *Advanced Robotics and Intelligent Automation* systems in the future. TIP envisions research and development in this critical national need area should:

Develop infrastructural solutions enabling Advanced Robotic and Intelligent Automation systems to seamlessly assist in, and perform more dangerous, dirty, dull, and difficult tasks leading to greater competitiveness through new levels of performance.

MAGNITUDE OF THE PROBLEM

The challenges facing the U.S. manufacturing sector have been a recurring topic of discussion for several years now. One challenge is that a paradigm shift has occurred whereby businesses are overhauling the way they manage supply chains, inventory, production practices, and staffing.[6] Storeowners do not order products unless the products can be sold quickly; manufacturers do not produce unless they have buyers lined up. This has resulted in the manufacturing sector facing financial challenges economists call a *jobless recovery*.[7] A jobless recovery (first used to describe the economic recovery of the early 1990's) is characterized by a job growth rate that is at best close to a net of zero because of sector restructuring; has low capital spending levels; and yet in spite of these conditions, has output levels that continue to increase due to productivity gains.[8] These observations are supported by data from the Federal Reserve Bank of St. Louis[9] [10] [11] [12] and the Bureau of Economic Analysis[13] [14] shown in Figure 1.

The data in Figure 1 represent recent production, capacity utilization, and employment trends for manufacturing, with times of economic recessions shown as vertical bars. Prior to the 1990 recession, employment reductions arose from temporary layoffs due to decreases in production and capacity utilization. Employer and employee both expected their working relationship to resume when economic conditions improved.

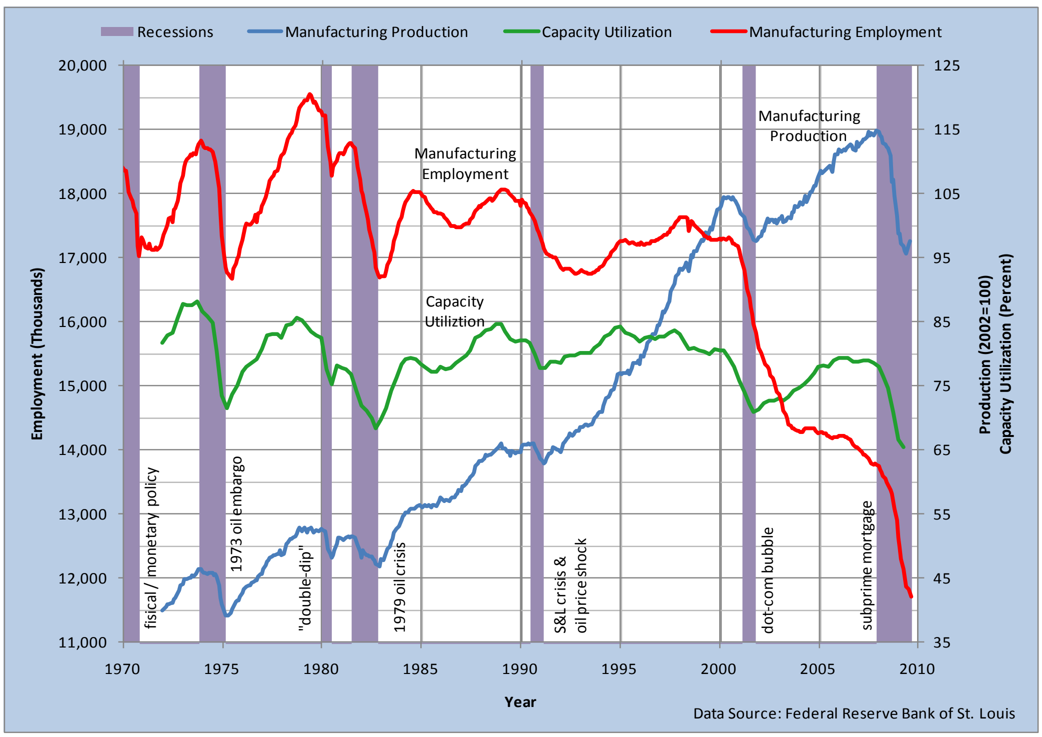

Figure 1: Recent manufacturing production, capacity utilization, and employment trends

However, after the 1990 recession, there were significant changes in the way the economy behaved. Manufacturing sector restructuring resulted in permanent job loss as employers tried to reduce costs.[15] Laid-off workers did not return to their previous jobs, but instead needed to be retrained with new skills for entirely new industries. Complicating this situation further, more and more employers chose as manpower staffing solutions temporary hires, outsourcing, or part-time labor rather than to rehire employees.

But employment issues are not the only challenges facing the U.S. manufacturing sector during these economic periods. After economic downturn periods, output and productivity return fairly quickly, but the recovery of capacity utilization is much slower. Capital spending is reduced in part because there is no incentive to invest in new equipment since excess capacity exists.

Technology-based solutions offer possible answers, but only if they can address output and productivity growth and can significantly improve manufacturing quality, capabilities and/or enhance competitive advantages (i.e., make manufacturers more successful).

The challenges facing the U.S. manufacturing sector are significant enough that they have been looked into and discussed by the Federal government and various national associations, e.g.,

- The President's Council of Advisors on Science and Technology (PCAST) recently asked the Science and Technology Policy Institute (STPI) to study[16] how to create new industries through science, technology, and innovation; and to discuss how to:
  - Achieve greater customization and scalability;
  - Furnish heterogeneous mixes of products in small or large volumes while exhibiting mass production efficiency and the flexibility of custom manufacturing;
  - Respond more rapidly to customer demands; and
  - Find better ways to transfer scientific and technological advances into processes and products.

- *A Framework for Revitalizing American Manufacturing,*[17] a policy paper from the White House, identified the need to support technological developments including:
  - Federal government investment in research for advanced manufacturing technologies; and
  - Advanced robotics that enable the retention of manufacturing in the U.S. and can respond rapidly to changes in consumer product demands.

- The National Science and Technology Council's (NSTC) Interagency Working Group on Manufacturing R&D, in their report *Manufacturing the Future,*[18] suggested that:
  - Future competitiveness depends in large part on research, innovation, and how quickly firms and industries can apply and incorporate new technologies into high-value-added products and high-efficiency processes; and
  - The ability to integrate new designs, processes, and materials in a modular fashion translates into competitive advantages that include shorter product development cycles, more efficient and more flexible supply chains, and new opportunities to deliver value-added products and services to customers.

- The report *Next Generation Manufacturing Study: Overview and Findings,*[19] developed by the Manufacturing Performance Institute on behalf of the American Small Manufacturers Coalition (ASMC), showed that:
  - There is a need to transform the manufacturing sector into a faster, more flexible set of industries capable of capturing global market share;
  - Small- and mid-size manufacturers lag behind larger manufacturers in implementing strategic and operational changes; typically facing higher hurdles due to the lack of the same levels of cash, time, and management depth as large firms; and
  - This resource gap constrains the ability of smaller firms to implement next generation manufacturing strategies, which will become more problematic as manufacturing continues to shift away from large, vertically integrated firms toward smaller and more nimble firms.

- *American Competitiveness Initiative*,[20] a report from the Office of Science and Technology Policy (OSTP), discussed the need for
  - Integrating new innovations into manufacturing/advanced manufacturing; and
  - Planning and control methods that lead to greater yields at faster cycle times than conventional approaches.

- *Manufacturing Resurgence: A Must for U.S. Prosperity,*[21] a report prepared for the National Association of Manufacturers (NAM), discussed manufacturing sector's reliance on innovation and investments that can raise productivity faster than other sectors.

All these studies point to the manufacturing sector's need for, and reliance on, technology innovation and the quest to identify novel science and technology solutions for advanced manufacturing. But these technologies are not easy to develop or to adapt broadly across industries. Examples of such innovations from the last 30 years include computer numerical controls (CNC), automated handling equipment, computer-aided design (CAD) and computer-aided manufacturing (CAM), just-in-time manufacturing (JIT) and total quality management (TQM).[22] These technology-based improvements to productivity have come primarily from information technology offerings. The logical question to ask is: From where will the next science and technology-based solutions come?

One could easily argue that the next revolutionary solution in manufacturing would be to improve the connection between information technology capabilities and the physical working environment. This could provide new levels of production quality and speed, new capabilities, and broader opportunities for products that could not be realized with current manufacturing methods. Speed, quality, capabilities, and opportunities all play crucial roles in estabishing competitive advantages in an increasingly globalized economy. For this reason and others, *Advanced Robots and Intelligent Automation* has been identified in the studies cited earlier as a viable next generation solution to achieving these objectives.

But today's robotics and automation systems are not yet ready to step in and play a leading role in these next generation solutions. As Bill Gates summarized in a recent article, today's robotics industry is still in its infancy, analogous to the computer industry of 30 years ago. The robotics industry is[23]

> *"An industry based on groundbreaking new technologies, wherein a handful of well-established corporations sell highly specialized devices for business use and a fast-growing number of startup companies produce innovative toys and gadgets for hobbyists and other interesting niche products. But it is also a highly fragmented industry with few common standards or platforms. Projects are complex, progress is slow and practical applications are relatively rare."*

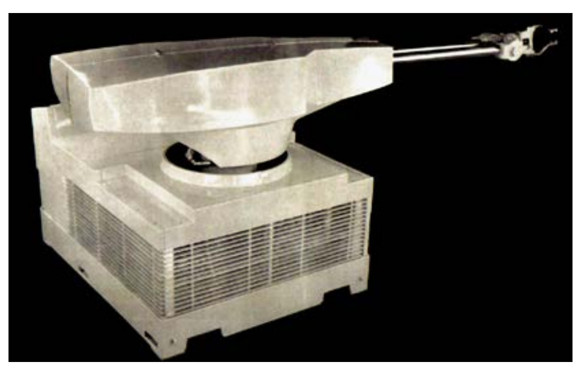

Figure 2: Unimate robot circa 1961

As evidence of this assessment, consider the industrial robot, which has not changed significantly since the 1961 introduction of the first Unimate robot (shown above[24]). This robot, installed at a General Motors plant in New Jersey, picked up castings from an assembly line and placed them onto vehicle bodies for welding. Robots at that time were viewed as a means of providing labor costs savings.

Today's modern industrial robot (shown to the right[25]) has seen improvments in areas such as computing capabilities and operational degrees of freedom. However, these robots are limited to operating in highly structured environments and exhibit low levels of autonomy. Today's industrial robots are essentially the tools of long production runs and large volume manufacturers (i.e., have a focus on mass *production* rather than on mass *customization*) and are considered components that perform essentially single operations in manufacturing.

Figure 3: Today's modern industrial robots

This assessment of the status of industrial robotics is supported by data from the International Federation of Robotics (IFR),[26] [27] which shows that robots are underutilized in the U.S. when compared to other leading manufacturing countries from around the world. Robot density, defined as the number of robots per 10,000 production workers, is perhaps the best measure of this underutilization.

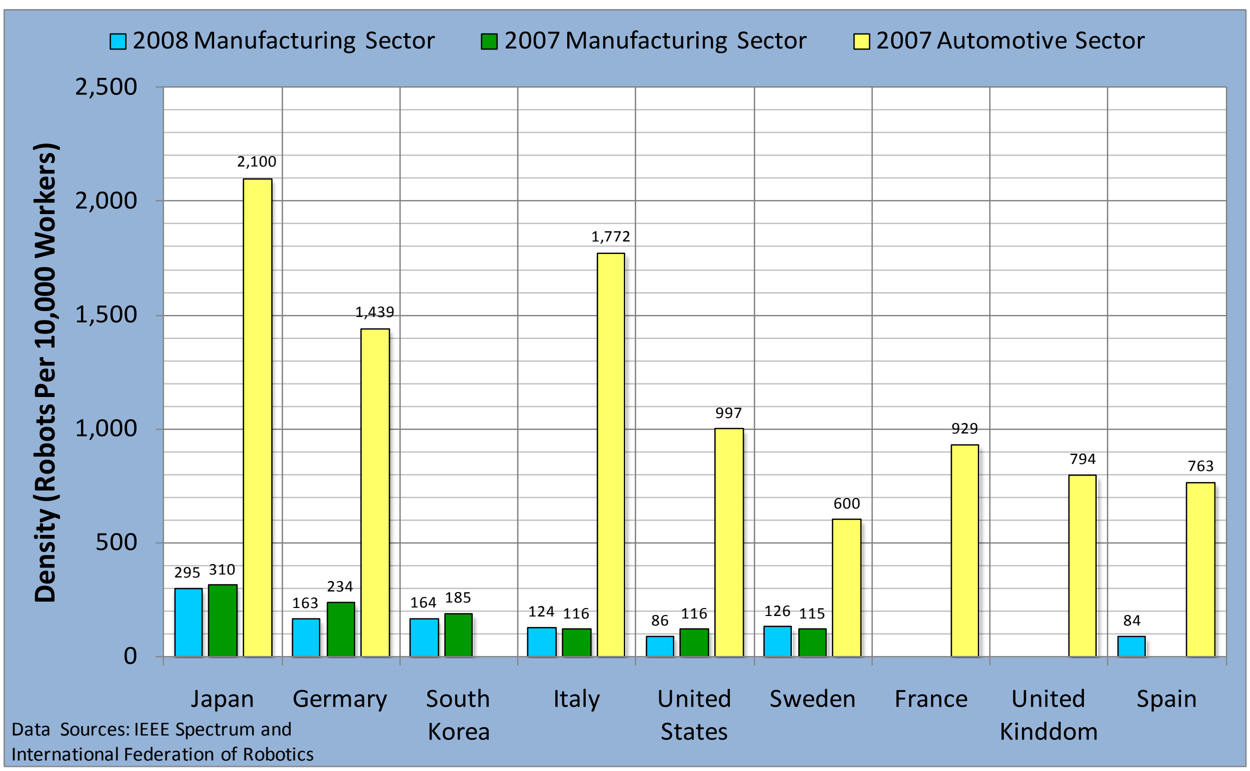

Figure 4: Robot intensity for various countries (some data not available for all countries)

In 2008 (Figure 4), the United States had 86 industrial robots per 10,000 production workers averaged over all sectors of manufacturing. This was down from 2007's 116 robot density and was about one-third of Japan's world leading robot densities of 295 and 310 for 2008 and 2007, respectively. This suggests that based on currently available technology, robots and intelligent automation systems could make greater contributions to U.S. manufacturing, based on Japan's robot density level in manufacturing.

However, it is unlikely that U.S. manufacturers will make any large investments soon. As an example, consider the automotive industry, which is currenly the largest user of robotics and automation. In 2007, the U.S. automotive industry's robot density was less than half that of Japan (997 vs. 2,100 robots per 10,000 workers). The IFR analysis concluded that as the U.S. automotive industry continues to further consolidate, Detroit's automotive manufacturers would likely only make new large investments in robotics if there were major technological advances.

But overseas automotive competitors such as Toyota and Honda are not standing still. They are investing in advances in robotics and intelligent automation systems for reasons that go beyond the needs of their core competency in automobiles and their manufacture. These companies see the potential for robots to be workers and co-workers. As workers, they can be integrated into manufacturing processes and perform multiple tasks. As co-workers, they can assist and provide humans with greater capabilities. This latter area of developmental opportunity arises from Japan's need to respond to its dwindling birth rate coupled to a rapidly aging population[28] and a desire to secure a stable labor force for manufacturing, eldercare and other needs.

This issue of dramatically changing population demographics is a problem also facing the United States. The U.S. Census Bureau[29] has developed population forecasts for the next 40 years, which are summarized in the following table and shown in Figure 5 on the next page. The working age group (ages 20 to 64) is projected to grow about 30 percent over the next 42 years while the retiree group (ages 65 and over) is projected to grow 128 percent. This translates into a population distribution shift that will go from 4.7 workers per retired person in 2008 to 2.7 in 2050.[30] With the ratio of workers to retirees projected to decrease from 4.7 to 2.7, there will be fewer workers available for manufacturing jobs as well as in other industries, such as healthcare and eldercare.

Year	United States Population				Ratio of Ages 20-64 to 65+ (Worker:Retiree)
	Ages 0 - 19	Ages 20-64 (Workers)	Ages 65+ (Retirees)	Total	
1950	51,673,000	88,203,000	12,398,000	152,274,000	7.1
2008	82,640,086	182,549,922	38,869,716	304,059,724	4.7
2050	112,940,253	237,522,850	88,546,973	439,010,253	2.7

This means that our nation's manufacturing sector will continue to face significant challenges from an availability of labor resources as well as from developmental, timeliness and urgency perspectives. A continual influx of new technical solutions will be needed to sustain productivity growth and a competitive position. Productivity growth is crucial to the U.S. economy because:

- According to the current Federal Reserve Chairman, productivity is perhaps the single most important determinant of average living standards;[31] and
- Productivity equals profitability; and productivity is raised through technology investment,[32] as shown in a study by the National Association of Manufacturers (NAM).

A TIP-proposed funding opportunity in *Advanced Robotics and Intelligent Automation* is a means to deliver the technical solution that could address a number of critical manufacturing needs, but because advanced robotics is an industry in its infancy with complex, cross-disciplinary engineering and scientific challenges, it needs nurturing to grow into its potential.

The industry needs to move away from the 1960's era one-arm assembly line robot that was considered to be a means of saving on labor costs into the next generation *Advanced Robotics and Intelligent Automation* systems that represent greater agility, flexibility, and autonomy in a way that enhances a worker's capabilities.

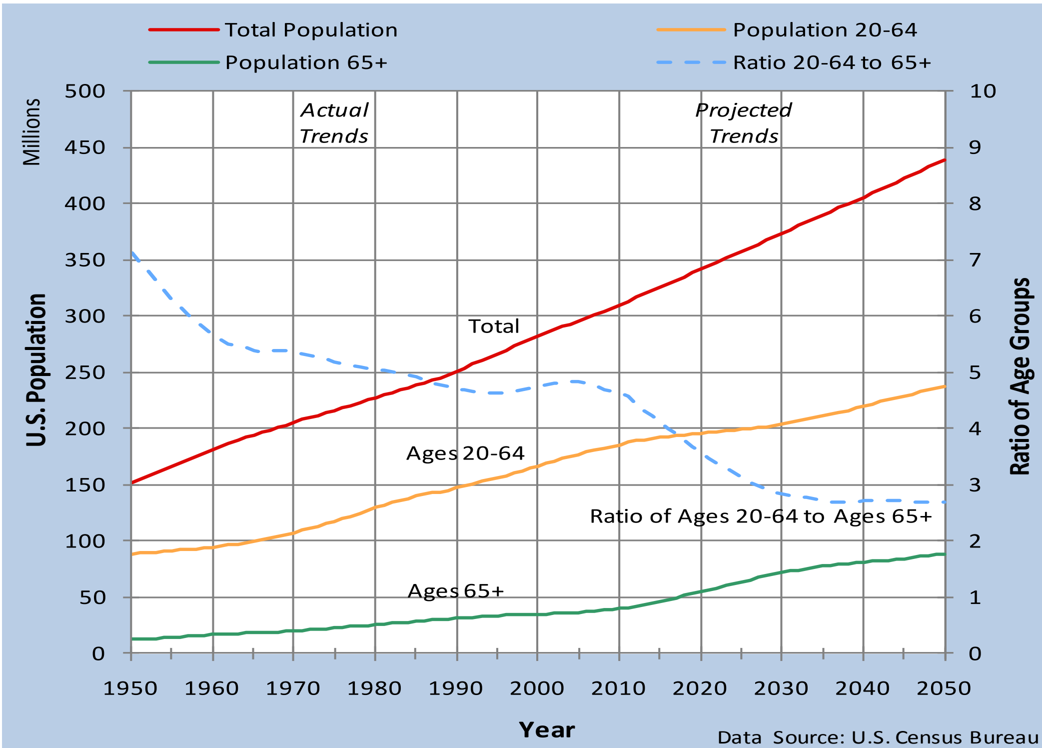

Figure 5: U.S. Census Bureau data for population trends

MAPPING TO NATIONAL OBJECTIVES

Both current and previous Administrations and congresses have recognized the importance of the manufacturing sector to the nation. For example, the Executive Office of the President recently published *A Framework for Revitalizing American Manufacturing* [33] in which the Federal government was called upon to invest in research with the goal of establishing U.S. leadership in advanced manufacturing technologies. Particular attention was given to developing "advanced robotics technologies that allows the U.S. to retain manufacturing and respond rapidly to new products and changes in consumer demand." Other references supporting the importance of, and need for, manufacturing can be found in:

- *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* by the National Academies of Science, Engineering and Medicine;[34]
- *American Competitiveness Initiative,* from the Domestic Policy Council of the Office of Science and Technology Policy;[35]
- *Manufacturing the Future*, National Science and Technology Council (NSTC), Interagency Working Group on Manufacturing R&D, Committee on Technology;[36]
- *Next Generation Manufacturing Study: Overview and Findings,* by the American Small Manufacturers Coalition;[37] and
- *White Papers on Advanced Manufacturing Questions* by the Science and Technology Policy Institute (STPI).[38]

The current Administration's 2010 budget identified science, technology, and innovation as critical tools for making progress toward the national goals of a prosperous economy, a clean energy future, a healthy American people, and a strong and secure America.[39] The Office of Science and Technology Policy (OSTP) provided an overview of the Administration's budget for next-generation manufacturing technologies in a memo entitled *A New Foundation for the 21st Century Technology Investments in the 2010 Budget*.[40] Additionally, in an effort to understand potential opportunities for economic growth and national security, OSTP has recently held meetings to identify synergies, technology challenges, and gaps in the current support for robotics by various Federal agencies and programs. The President has expressed his personal views on robotics in a recent speech to Virginia high school students, stating "robotics can inspire young people to pursue science and engineering."[41] And finally, in a memorandum on *Science and Technology Priorities for the FY 2012 Budget*,[42] the Administration has recognized advanced manufacturing and robotics as a means to support one of the six challenge areas that need strengthening, specifically: "Promoting sustainable economic growth and job creation."

Congress also has expressed interest in understanding the area of robotics, launching the Congressional Caucus on Robotics on June 20, 2007.[43] The caucus focuses on key issues facing the nation's traditional industrial robotics industry, issues critical to growing companies and markets through technological advances, and issues associated with enabling robots to operate in environments that go beyond the traditional factory floor. As of December 2009, there were over 30 members.

NIST Laboratory Activities

The mission of the Department of Commerce (DoC) is to advance economic growth and jobs for the American people. DoC has crosscutting responsibilities in areas of trade, technology, entrepreneurship, economic development, environmental stewardship and statistical research and analysis. The National Institute of Standards and Technology (NIST), an agency within DoC, is charged with promoting U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.

In support of this mission, NIST research and development is involved in the area of *Advanced Robotics and Intelligent Automation* through a number of initiatives. The Manufacturing Engineering Laboratory's (MEL, now part of the NIST Engineering Laboratory[†]) mission is to "promote innovation and the competitiveness of U.S. manufacturing through measurement

[†] On October 1, 2010, NIST realigned its laboratories according to a mission-based structure. Further details can be found at http://www.nist.gov/public_affairs/factsheet/reorg_factsheet.cfm

science, measurement services, and critical technical contributions to standards." Within MEL, the *Intelligent Systems Division* supports "a future in which U.S. manufacturing grows more accurate, agile, intelligent, interoperable, and reconfigurable through constant innovation" and is responsible for developing measurement and interoperability standards that will enhance manufacturing robotic and automation equipment and the underlying industrial control systems. MEL activities include…

- Involvement in over a dozen and a half projects that include working with Department of Defense laboratories and manufacturers;[44]

- Hosting manufacturing and robotics workshops (as recently as November 3-4, 2009[45]);

- Supporting *Agile 21st Century Manufacturing for the Innovative Products of the Future* through robotics and automation that are "versatile, quickly reprogrammable, and work safely in collaboration with, and in close proximity to, humans; tirelessly augmenting human abilities with strength, high precision, and repeatability to attain smart assembly;"[46] and

- Working in conjunction with other NIST laboratories such as Building and Fire Research (BFRL, now part of the NIST Engineering Laboratory), Electronics and Electrical Engineering (EEEL, now part of the Physical Measurement Laboratory), Information Technology (ITL), and the Chemical Science and Technology (CSTL, now part of the Material Measurement Laboratory) Laboratories, laboratory collaborations works to develop measurements and standards in support of robotics.[47]

Other NIST laboratory activities also support relevant technologies:

- ITL's *Pervasive Information Technology Program* is addressing trends towards increasingly ubiquitous connected computing sensors, devices, and networks that monitor and respond transparently to human needs; the *Information Discovery, Use and Sharing Program* supports three dimensional shape searching and imaging.

- NIST has made assessments of the U.S Measurement System (USMS)[48] and has identified intelligent robotic systems for manufacturing, defense, and homeland security as a need. Specific examples include victim recognition for fire fighting and search and rescue; human-robot interactions in a working environment; manufacturing at the nano-, meso-, and micro-scales; robotic surgical tools; and construction automation.

NIST's involvement in these activities further highlights the importance of these areas. NIST laboratory support of measurements and standards in *Advanced Robotics and Intelligent Automation* is seen as crucial to the future development and growth of this nascent industry and would be synergistic to TIP's support of high-risk, high-reward research opportunities.

MEETING TIMELY NEEDS NOT MET BY OTHERS

As the *Magnitude of the Problem* discussion above has shown, the manufacturing sector has not fared well under the current economic climate. Yet manufacturers continually need to develop new technical capabilities to be competitive. The manufacturing sector's support for new high-risk, high-reward technology, however, is limited or non-existent. This support is even worse for the advanced robotics industry, which is in its infancy with weakly defined technical directions.

Industrial robots have not changed significantly since their invention in the 1950's and subsequent commercialization in the early 1960's. Funding can be found for unmanned systems within the defense industry, but very few programs have been established in the commercial, industrial or healthcare sectors. When support is available, agencies such as the National Science Foundation (NSF), National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD) laboratories generally support either basic research in new technologies, specific solutions in support of mission requirements, or solutions that are experimental in nature.

This means that while robots are being built, many potential users find that they are too expensive to purchase and operate, often have to be designed from the ground up, and do not have general applicability. To overcome these issues requires support for infrastructural technology development and validation. The technical elements that can form an infrastructural solution fall into the following broad categories, and will be discussed in the section on *Societal Challenges*:

- Dexterous manipulation;
- Concurrency (parallel activities);
- Navigation and 3D planning;
- Technology integration;
- Power and energy systems;
- Wireless communications; and
- Safety and human-robot interaction.

But support is needed not just to satisfy technological requirements, but also for timeliness issues. As discussed in the *Magnitude of the Problem* section, the forecast for changes in the United States population shows there will be a need for co-workers to not only support manufacturing, but also for healthcare and eldercare needs. The timeline for this need is projected to begin in the next several years and continue for the next 20 to 40 years. Solutions therefore need to begin development now and undergo validation and the early stages of commercialization in order to be available when needed. There is also a competition with offshore companies.

Overseas competitors such as Toyota and Honda also are looking into these new robotic capabilities. Honda has even gone so far as to publically acknowledge robotics as a strategic capability. Korea[49] has launched a 21st century frontier initiative, committing to invest a billion dollars in robotics technology over the next ten years. Similar, but smaller programs are also in place in Australia, Singapore, and China.

In summary, TIP's support of *Advanced Robotics and Intelligent Automation* satisfies a timely need that is not currently being met by others within the critical national need area of manufacturing or in complementary areas such as healthcare, eldercare, or homeland security.

SOCIETAL CHALLENGES

The ability to build next generation *Advanced Robotics and Intelligent Automation* systems currently faces many high-risk, high-reward research challenges. One of the most important needs is to develop broadly enabling solutions that are infrastructural in nature and will support future growth. But the developers who would undertake this challenge are members of a fragmented industry that is still essentially in its infancy. End users, another set of stakeholders, are in the midst of sector restructuring. And the desired advanced solutions require input from cross-disciplinary teams of engineers and scientists. Consequently, limited support is available and typically focuses on mission-specific solutions. All this can be summarized by the following societal challenge:

***Advanced Robotics and Intelligent Automation requires the development of infrastructural technologies that are broadly enabling and far-reaching, or next generation manufacturers will not have access to solutions that can provide needed new levels of precision, quality, agility, flexibility, and safety*.**

The technical elements that need to be developed can be broadly grouped into three categories. These three categories generally follow technical groupings from U.S.[50] [51] and European[52] robotics industry roadmaps and represent high engineering and scientific risk. High engineering risk typically means successful integration of complex or newly developed systems is not assured due to technical challenges – not cost. High scientific risk means successful advances in sensor technology or computing improvements are not assured due to scientific barriers – not cost. The first two of the three technical elements contain high-risk, high-reward challenges that are appropriate for TIP support. The three technical elements are:

1. Critically needed solutions in which the robotics industry can lead development efforts;
2. Critically needed solutions in which the robotics industry can leverage solutions from other industries; and
3. Solutions that need to be developed by the robotics industry on their own.

Each technical element is presented in more detail below. Each technical element contains specific technical concept areas that include the desired capabilities and desired developments for each technical concept area. For Elements 1 and 2, the desired developments are discussed in terms of short and long-term opportunities and either time frame may contain high-risk, high-reward opportunities. The "short-term" timeframe represents technological needs approximately 5 years into the future, and the "long-term" timeframe is 10 to 15 years into the future.

Element 1: Critically needed solutions in which the robotics industry can lead development efforts consist of the technical elements of dexterous manipulation, concurrency, navigation and three-dimensional planning, and technology integration.

- **Dexterous Manipulation** (use of end effectors) is the ability to (skillfully) operate on objects. Today's robots typically focus on single tasks based on a gripper that can operate on objects with specific properties (usually rigid and known shape). Robotics drives the development of grippers, hands, process tools and tool changers as well as sensors (e.g., skin sensors) and some sensor properties (e.g., size, weight, and safety). The prostheses industry also is involved as both a contributor and end user.

Desired capabilities: Dexterity and strength that allows for higher speed and precise manipulation of a variety of objects; able to use fingers and multiple coordinated end effectors; and can handle objects that range in scale from nano to hundreds of meters.

Desired developments: In the short term, task-specific end effectors will be mostly pre-programmed or taught grasping strategies; task-specific sensor fusion will rely on calibration and will be limited by computer processing power. In the longer term, grasping operations will be computed online; advances will be needed to greatly improve three-dimensional vision sensors for dexterous hands and grasping of all objects; and the implementation of multiple visual processes on sensor or dedicated processors as well as multimodal sensing for intrinsic safety. Key developments will be associated with processing capabilities and sensor integration.

- **Concurrency** (performing multiple activities in parallel) is the ability to communicate with and coordinate multiple autonomous robot systems in order to achieve desired collective behavior from robot-robot interactions and interactions with the environment. Robotics is the driver for developments in concurrency, exclusive of communication and sensor network developments.

  Desired capabilities: Networked robots will allow tasks to be decomposed in ways that exceed human capabilities through seamless communications and synchronizations; cooperation between multiple robots achieves a common goal by carrying out the task together or by decomposition. They can interact directly or through the modification of the environment. The robots may access information gathered by teammates or from other sources. Robots with manipulators work together in close proximity,.

  Desired developments: In the short term, teams of robots will use centralized control and communication; tasks will be specified for individual robots. In the longer term, cooperation will be achieved without explicit representation of actions and will use skill-based or learning-based automation. Solutions could be based on distributed or cloud computing, multi-threaded programs on multi-core processors.

- **Navigation and Three-dimensional Planning** (and the related elements of perception and modeling) consist of several related parts. *Navigation* is concerned with controlling movement and relies on mapping, localization, and collision avoidance, which is different from map-based navigation. Combining localization and mapping with collision avoidance is robotics driven. *Planning* is the computation and selection of paths, motions, actions, tasks, policies, procedures, and missions for goal-directed robot behavior. Because optimization of planning is application specific, robotics can leverage results from other industries but ultimately must lead its own efforts. *Perception* is the ability to build and interpret representations of the physical world from sensed data; performing this under real-time constraints and fusing possibly uncertain information from many sources is robotics driven. *Modeling* is the mathematical approximation of reality. Robotics has a strong need to model and simulate the system (mechanics, actuators, electronics, and sensors) and the environment at runtime.

  Desired capabilities: Advanced robotic systems will need to be able to move through unstructured environments to accomplish their tasks. This is not just moving the robot to a new location, but also the ability to use multiple manipulators while not colliding with other objects or itself. Planning and control developments represent some of the greatest challenges in robotics. Even with perfect sensing and hardware, robotic planning and control fall well short of human performance in most tasks.

Desired developments: A progression of changes will need to occur in computing and sensors. Improvements in perception and sensors will be needed to enable operation in unstructured environments and greater opportunities to interact with their surroundings. Advances will be required in technologies for ranging, locating and identifying, as well as giving robots greater awareness of their surroundings. In the short term, solutions will be computationally expensive with solutions developed for localization and mapping in controlled environments. Planning will rely on manual programming based on human experience. Sensor fusion for perception is task-specific, relies on calibration and is limited by processing power. Lack of standards for model descriptions will slow development; simulation will not be as good as real-world experiments and will require long computation times. In the longer term, Simultaneous Localization and Mapping (SLAM) for challenging environments will be developed and collision avoidance will consider dynamic objects. Eventually, SLAM will work in unconstrained environments and collision avoidance with dynamic, non-cooperative obstacles will be through perception. Planning will progress from automated mission and process planning using databases of expert knowledge to online planning for tasks of high dimensionality that can be learned from human interactively. Perception will rely on advanced task-dependent sensor fusion with known events interpreted. Eventually, perception techniques take over from fusion, sensing will be on a chip and will no longer be task-dependent. Real-time, dynamic modeling and interpretation will allow for accurate assessment of the robot’s and the world’s state and will use higher frame rate visual sensors and greatly improved three dimensional vision sensors.

- **Technology Integration** is challenging because robots are complex systems requiring simultaneous scientific and engineering advances in multiple areas. Developing integrated platform-independent scientific and engineering solutions requires cross-disciplinary teams. For example, new manipulators or motion systems also depend on advances in power and energy systems. Navigation depends on sensing systems, computing and mobility systems. And these components somehow must all work together reliably.

  Desired capabilities: There are three issues associated with this element: system architecture, system engineering tools, and configurations. Architecture defines the system component’s structure, interrelationships, and principles governing the design. System engineering tools design robotic systems (hardware and software) and include simulation of a robot’s dynamic properties and deployment. And finally, configuration is the ability to make changes to a robot (or to the larger system).

  Desired developments: In the short term, architectures will be hierarchical and run on a single system that may use multiple computer cores for specific purposes. Separate system engineering tools will exist to aid in designing robots and applications and will be based on simplistic models that cannot be linked together. Configuration is carried out for a specific task or system at setup or between different tasks by online and offline programming. In the longer term, architectures will be based on hybrid or layered, service oriented approaches that will eventually be self-configurable, globally distributed, and resource-aware. System engineering tools will be integrated to design robots and applications based on dynamic robot models; eventually leading to tools that will be integrated and based on easy-to-use dynamic models for both robots and the environment, resulting in custom-build robot designs. Configuration will be simplified through improved user interfaces using more human-compatible modalities, eventually leading to life-long adaptation that minimizes the need for manual configuration.

Element 2: Critically needed solutions in which the robotics industry can leverage solutions from other industries consist of the technical elements power and energy systems, wireless communications, and safety and human-robot interaction.

- **Power and Energy Systems** (power management) are vital to mobile and autonomous robots. Currently available systems limit the capabilities of existing robots, which can have intermittent high power demands because they are computationally intensive, require multiple sensors to interact with the environment, and exhibit power spikes when performing tasks or moving. Many of the developments needed for robotics are currently being driven by the transportation and consumer electronics sectors.

  Desired capabilities: Energy and power represent complex problems whose solution depends as much on the energy and power systems as on the robotic systems that use the energy and power. Energy storage requirements can be relaxed if energy can be harvested in the field, but harvesting must be well-matched to consumption. Two issues are associated with energy harvesting: mechanisms for energy location and acquisition; and algorithms for power management and energy-seeking behaviors. Energy storage requirements also can be relaxed if the robot is more energy efficient. Efficiency involves improved components such as actuators and valves, energy recovery (elastic and/or regenerative), and algorithms for power management.

  Desired developments: New power and energy systems need to be scaled to robot-relevant sizes and need to be able to efficiently generate, store, and condition power. Scaling down for energy is often constrained by chemistry while power is constrained by device design. In the short term, solutions will use external power or local storage with options for regenerative braking available. In the longer term energy and power solutions will include wireless power transmission, inductive charging, fuel cells and solutions that focus on robotic system efficiencies. Energy conversion and generation will be local while regeneration is standard and planners conserve energy. The eventual target will be efficient wireless power transfer with increased robotic system efficiency and energy harvesting capabilities.

- **Wireless communications** and networking are required whenever robotic systems are distributed spatially, data or computing resources are remotely located and must be accessed, or whenever human interaction is required. Advances in communications and networking will lead to more capable, more robust, and more easily deployable systems. Open frameworks for software and hardware also will play an important role. The robotics industry can leverage and adapt solutions from aerospace and the consumer electronics industry to robotics, but this is non-trivial and needs support.

  Desired capabilities: Robots that are mobile within a factory environment will need to communicate with other robots and with supervisory control systems and potentially with wireless sensors around the factory. This is very challenging because of the electromagnetic environment where robots will be operating. Advances in wireless communications will be critically tied to developments in power and energy enabling autonomous movement as well as concurrency.

Desired developments: The challenge for this element will be to leverage developments from other industries to the specific needs of robotic systems. In the short term numerous specialized protocols will exist. Protocols for sparse, highly volatile multi-hop, ad-hoc networks with high bandwidth and low latency will develop. There will be improvements in localization for ultra-wide bandwidth networks and better spectrum utilization. Integration of wide-area, local-area, and personal-area networks will occur for more seamless local-to-global coverage (heterogeneity). In the longer term, new protocols will use ontologies (formal representations of knowledge by sets of concepts within a domain), logic, probabilistic or geometric models, and rule sets. Components will figure out each other's protocols and negotiate the required quality of service.

- **Safety and Human-Robot Interaction:** With next generation robots having greater mobility and interaction with their environment, a new level of safety will be required. Methodologies from other industries should be leveraged for robotic system safety. Human-robot interaction is the ability to mutually communicate between a robot and a human. The interaction can be multi-modal using sounds, gestures, or physical interaction.

  Desired capabilities: Ultimately, a key driver will be the ability to build lighter components leading to safer operation. Interactions will require perceptual awareness of people and actuators and robots that are intrinsically safe for humans to physically contact. Interactions between robots and ordinary people will require robots to pick up on social cues from humans and give social signals about their own intentions that people can readily interpret.

  Desired developments: In the short term, robotics will use sensor-based physical safety; hardware safety will be through redundancy, and software safety will be through formal approaches to programming. Humans will interact and communicate with robots using mostly graphical or text-based interfaces. Haptic (tactile) devices will be rare. In the longer term, model-based hardware and software failure detection and isolation will be implemented. Predictive failure detection will be possible, along with safe automatic obstacle avoidance and detection of people's intention. Communication and interaction will utilize cognitive approaches, neural interfaces, and non-invasive brain interfaces.

Element 3: Solutions that need to be developed by the robotics industry on their own consist of technical elements such as actuation systems and fabrication and materials technologies.

- **Actuation Systems** generate forces and torques that create a robot's movement. The robotics industry only drives the development of specialized parts such as lightweight, compact drives and gears designed for frequent speed and direction changes.

  Desired capabilities: Current actuators can be made to achieve good performance in a few requirements, but not good overall performance. This deficit has led to heavy, slow, fragile robots, which are dangerous for people to work with. Lighter actuators with built in sensors such as contact and level of exertion will be needed.

  Desired developments: Short term solutions will be based on electric, pneumatic, or hydraulic motors; and will be lightweight and use standard gears. Longer terms solutions will use continuously variable transmissions and exhibit improved energy savings and power-to-weight ratios. Micro-actuators and smart materials eventually will become leading solutions.

- **Fabrication and Materials Technologies** are concerned with robotic parts and systems and what is used to make them. Since materials research and development is driven primarily by other industries; robotics will greatly benefit from technology transfer, particularly in composites, lightweight metal foams, and materials integrating functionality such as sensing and actuation.

  Desired capabilities: Advances in fabrication and materials technology will enable novel lightweight, safe, low cost, compliant, and durable structures. Integrated fabrication technologies will result in compact, lightweight sub-systems that are rugged and have high performance. Smart material technologies will lead to compliant wearable sensors that either form robot skin or are placed on humans for measurement. Development of new materials will yield lightweight, soft and safer robotic structures enabling higher performance, and more agile robots.

  Desired developments: In the short term, solutions will involve shape memory alloys and electro-active polymers; there will be some use of carbon, composites, and metal foams. In the long term, shape memory alloys and electro-active polymers will enable robots to reconfigure themselves. Eventually nanomaterials will be used, as will intelligent materials and structures.

A fourth element covers other general technology developments needed for *Advanced Robotics and Intelligent Automation* systems. These needs do not appear to be infrastructural, but are more application/design specific and will occur in areas such as locomotion, robustness and reliability design requirements, and sustainability. They are an important consideration in that they have to be available and ready to integrate with the systems and components outlined in the three elements above.

ANALYSIS OF COMMITMENT

Potential participants, including small- and medium-sized companies, universities, national laboratories and other organizations, have indicated interest in the challenges described in the first two technical elements, and have capabilities or relevant experience to develop and validate.

- In Element 1, solutions that have been discussed include:
  – New techniques for dexterous manipulation and handling objects;
  – New approaches for navigation in unstructured environments;
  – New strategies for monitoring and controlling groups of robots; and
  – New technologies and approaches for the seamless integration of the various subsystems that make up a robot or intelligent automation system.

- In Element 2, solutions that have been discussed include:
  – New power and energy storage technology;
  – New approaches to communication;
  – New sensor technologies; and
  – New methods for ensuring safe interactions between robots and humans.

As further evidence of commitment, TIP has received a number of white papers directly related to the manufacturability of materials. Additionally, groups are loosely forming collaborations for the development of new solutions, but finding funding is proving to be difficult. TIP also has received a number of proposals in response to recent solicitations in the critical national need area of Civil

Infrastructure that included solutions based on robotics. Other examples of interest and commitment include:

- The Robotic Technology Consortium (RTC), which was formed by the National Center for Manufacturing Sciences (NCMS) as a not-for-profit subsidiary to speed development and deployment of innovative defense ground robotics technology. As of November 2009, there were 184 members.

- Massachusetts Technology Leadership Council (Mass TLC), which was formed in 2005 to raise awareness of the region's robotics industry throughout the U.S. It consists of over 100 companies and universities. http://www.masstlc.org/clusters/robotics.html

- The Computing Community Consortium (CCC, http://www.cra.org/ccc/) and the Computing Research Association (CRA, http://www.cra.org/) with over 200 members in academia, government and industry, focus on a variety of topics, including robotics.

These groups' interest in *Advanced Robotics and Intelligent Automation* means that there are pre-existing channels of communication for TIP to discuss its interest in this topic.

SUMMARY

The Technology Innovation Program was formed to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of critical national need. This research should address societal challenges, i.e., problems or issues confronted by society that when not addressed could negatively affect the overall function and quality of life of the nation, and as such demand government attention.

The manufacturing sector is an example of such an area and is in need of novel and innovative solutions both to overcome the manufacturing sector's latest economic setbacks as well as to establish new levels of global competitive advantages. *Advanced Robotics and Intelligent Automation* represents the potential to support technical solutions that could provide a new level of agile and flexible capabilities to an industry that has historically focused on long production runs and large volume manufacturing. The infrastructural technology developments outlined in this paper would enable the development of the next generation of advanced robotic systems capable of also providing greater precision and quality needed to move automation into smaller volume manufacturing, and creating better, higher pay jobs.

A few companies (such as Marlin Wire[‡] in Baltimore, Maryland) have demonstrated the ability to respond to short timeframe market demands and create good paying quality jobs through the use of robotics,[53] [54] and offer the following important lessons:

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‡ In 1998, Drew Greenblatt sold a small home security alarm business and bought a 30-year-old Brooklyn, New York company that made wire baskets and racks. Employees of the company at that time made minimum wage and had no health insurance or retirement plan.

In 2000, the company had moved to Baltimore, Maryland and was facing overseas competitors with low labor costs who were dominating the wire basket market. Marlin Wire tried to reinvent itself by targeting precision baskets and steel wire products for industrial applications, but hand bending and welding baskets meant the baskets could not be made to the necessary tolerances.

> Unlike Marlin Wire, Chinese manufacturers require large minimum orders and long lead times. "China can't get a custom single hook or single basket in less than a week… They can't do it." Further, the company president reported that "if your company is using robotics to improve product quality, increase productivity, speed time to market, and reduce manufacturing costs, you know there's a chance to remain competitive, keep jobs here, and grow in the future."[55]

This viewpoint is growing, as evidenced by a recent report from the Economic Policy Institute.

> "U.S. firms can and do compete with China and other low-wage countries, in part because direct labor costs are only 5 to 15 percent of total costs in most manufacturing. U.S. companies can continue to pay higher wages for direct labor and offset the added cost with greater capabilities, capabilities that lead to outcomes such as higher productivity, fewer quality problems, and fewer logistical problems."[56]

The major difficulty in performing the research needed to accelerate the development of these technologies is that current financial resources are both inadequate and skewed relative to what is needed. In particular, advanced manufacturing needs system level technical solutions, which are coupled with the need for advances in specific elements of that system in response to system level productivity requirements. This level of development is typically well beyond the scope of a single company or university research investment. Researchers may invest in specific components, but without the coordination at the system-level, private sector investment will be suboptimal.

Further, without support, technical solutions will not be developed in a timely fashion. The issue of timeliness manifests itself in at least three ways:

- The manufacturing sector has a need to create new productivity and competitiveness opportunities, which is reliant on introducing new technological capabilities. This relates to lead time requirements to develop manufacturing and assembly technologies for current products as well as for new nano- and micro-scale products being developed today. (This latter point is analogous to what Andy Grove, former CEO of Intel, described for the first computer memory chips.[57])

- There is also an urgency associated with meeting the demands that will be placed on society based on the Census Bureau's forecasts for changing population demographics and the need for more co-workers and assistants in support of manufacturing, healthcare and eldercare.

- Investing now in the technologies for *Advanced Robotics and Intelligent Automation* will support the structural repositioning of the U.S. manufacturing sector in a manner that will

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The solution was to invest in used robotic welding and bending machines that were run by AutoCAD software. The company concentrated on the engineering of custom-made, high-quality, short turnaround steel wire products for other manufacturers. In 2002, such jobs made up less than one percent of the company's sales. By 2007, they were more than 95 percent. The improvement in manufacturing capabilities meant that each employee could now be offered health insurance and retirement plans.

enhance the nation's ability to withstand future economic shocks and to foster sustained and vibrant economic growth.

TIP's support of this research and development topic represents an opportunity to address an important societal challenge in the critical national need area of manufacturing, a funding gap in the needed support, and solutions that can be well-timed. This effort would be synergistic to the research work in measurements and standards that NIST laboratories are undertaking as well as supportive of the needs of other Federal agencies such as the Departments of Defense, Homeland Security and NASA.

APPENDIX 1: LIST OF SUPPORTING ROADMAPS FOR THIS TOPIC

- *A Roadmap for US Robotics: From Internet to Robotics,* May 21, 2009, Computing Community Consortium (CCC)
  NSF sponsored roadmapping effort by universities and companies, addresses the technical needs of half a dozen application areas
  http://www.us-robotics.us/reports/CCC%20Report.pdf

- *Robotics in Manufacturing Technology Roadmap,* November 2006, Energy Industries of Ohio
  Discusses the application of small lot and flexible robot systems in manufacturing; industry stakeholders outlined critical barriers to increasing the use of robots, and provided their thoughts on the research, development, and other activities needed to overcome those barriers
  http://www.energetics.com/resourcecenter/products/roadmaps/Pages/Robotics-inManufacturing-Roadmap.aspx

- *Unmanned Systems Roadmap (2007-2032),* December 10, 2007, Dept. of Defense
  Discusses DOD's efforts in unmanned vehicles
  http://www.fas.org/irp/program/collect/usroadmap2007.pdf

- *The National Plan for Research and Development In Support of Critical Infrastructure Protection,* 2004, Office of Science and Technology Policy, Dept. of Homeland Security
  Discusses the use of passive and active sensor systems with robotic platforms to monitor and protect the nation's critical infrastructure
  http://www.dhs.gov/xlibrary/assets/ST_2004_NCIP_RD_PlanFINALApr05.pdf

- *A Roadmap for the Robotic and Human Exploration of Mars*, May 2005, NASA
  Outlines how NASA can build on its existing robotic Mars Exploration Program to enable future human expeditions to Mars
  http://images.spaceref.com/news/2005/srm2_mars_rdmp_final.pdf

- *The Intelligent Systems and Robotics Center,* 2006, SANDIA
  Discusses the activities of the Intelligent Systems and Robotics Center (ISRC) which was focusing on extreme mobility solutions
  http://robotics.sandia.gov/home.html

- *Roadmap envisions future of robotics,* March 12, 1999, SANDIA
  Discusses SANDIA's plans for micro-robots
  http://www.sandia.gov/LabNews/LN03-12-99/robot_story.htm

- *Robotic Visions to 2020 and Beyond*, July 2009
  Discusses Europe's technology roadmap for robotic developments
  http://www.robotics-platform.eu/cms/upload/SRA/2010-06_SRA_A3_low.pdf

- Portal to European Healthcare (includes robotics)
  Links to discussions of robotic healthcare assistance and needs/activities in the European Union
  http://www.ehealthnews.eu/

APPENDIX 2: LIST OF SUPPORTING WHITE PAPERS

A. White papers submitted to TIP

- *Closing The U.S. Labor Force Gap: The Case for Government Support of Robotic STEM Education Technologies* -- iRobot Corporation
  Discusses education and training requirements for the next generation of robot operators

- *Vision Guided Robotics, Retrofit Simulation Guidelines* --- Braintech
  A plan for retrofitting manufacturers with vision-guided manufacturing robots

- *Coordinated Agile High-velocity Vehicle (CAHV)* --- Vecna Technologies, Inc.
  Discusses a novel vehicle using a combination of walking and wheels for motion

- *Mapping in Complex Urban Terrains* --- Vecna Technologies, Inc.
  Discusses mapping and vision (3D camera) system requirements in urban environments

- *Transforming Autonomous Mobile Sentries (TAMS)* --- Vecna Technologies, Inc.
  Discusses the technical needs of sentry robots for border patrol

- *Extending Independence: The Case for Federal Support for Robotic Caregiving Technology* --- iRobot
  Discusses how robots could be used to assist a population with a growing number of senior citizens and what the technical needs are

- *Developing Safe Robot-Human Interaction* --- Vecna Technologies, Inc.
  Discusses the technical needs for assistive robots in unstructured, human environments

- *Wireless Visual Sensor Networks for Urban Traffic Management* --- University of Texas at Austin
  Addresses traffic flow issues through new sensor development

- Automatic Person Detection and Tracking from a Moving Platform --- Vecna Technologies, Inc.
  Discusses a new tracking algorithm for partially obscured objects

- *Industry – Academy Collaboration in Cyber Physical Systems (CPS) Research* --- George Mason University Cyber Physical Systems (CPS) are engineered systems comprising interacting physical and computational components; discusses the need for collaboration to advance the technology
  http://www.cra.org/ccc/docs/CPS-White%20Paper-May-19-2009-GMU-v1.pdf

- *Automatic Sign Recognition for Enhanced Navigation, Awareness and Localization* --- Vecna Technologies, Inc. Technology to automatically recognize signage

- *Achieving Ubiquity, Timeliness, Accuracy, And Reliability In Nextgen Traffic Information Systems* --- University of California at Berkeley, California Center for Innovative Transportation
  Discusses opportunity to develop technologies for automated traffic control from complex network perspective

B. White papers submitted to the NSF sponsored workshop by CCC/CCR

- *Robotics* --- Georgia Institute of Technology
  Discusses the current state of robotics and provides insights into conclusions of the roadmap *A Roadmap for US Robotics: From Internet to Robotics,* May 21, 2009
  http://www.us-robotics.us/robotics-essay.pdf

- *Robotics* --- Massachusetts Institute of Technology
  Discusses why robots are needed, state of the art, and what needs to be done to move the technology forward
  http://www.cra.org/ccc/docs/init/Robotics.pdf

Manufacturing Robots

- *Challenges In Robotics Toward Cyber-Enabled Multi-Scale Multi-Paradigm Life Science Automation* --- University of Tennessee at Knoxville
  Discusses automation needs in life sciences.
  http://www.us-robotics.us/man-proposals/1-CyberEnabledLSA-Zhang&Hamel.pdf

- *Parallel and Stochastic Processes in Manufacturing from Nano to Macro Scales; CAD for Biomimetic Manufacturing* --- University of Washington
  Use of robotics for parallel processing in manufacturing, also discusses modeling tools
  http://www.us-robotics.us/man-proposals/2-NSF-CCC-2008-Bohringer.pdf

- *Proposal* --- GM R&D Manufacturing Systems Research
  Discusses GM's history with industrial robotics, what they are looking for in future developments
  http://www.us-robotics.us/man-proposals/3-GMR&DMSR-Wells.pdf

- *An Infrastructure Free Automated Guided Vehicle Based on Computer Vision* --- Carnegie Mellon University
  Discusses robotic needs in materials handling logistics
  http://www.us-robotics.us/man-proposals/4-Free-Automated-Guided-Vehicle-CMU-Kelly.pdf

- *Research Areas of Interest for General Electric* --- GE Global Research
  Discusses mobile, high degrees of freedom (DOF) robots on manufacturing facilities floors
  http://www.us-robotics.us/man-proposals/5-GE-NSF_RoboticsWorkshop_v3.pdf

- *Measurement Science Foundations For Next-Generation Manufacturing Robotics* --- NIST
  Discusses measurement needs in support of standards development for robotics
  http://www.us-robotics.us/man-proposals/6-CCC-submission-NIST-ISD2-Messina.pdf

- *A Research Roadmap for Robotics in Manufacturing and Automation* --- University of Utah
  Robotic design needs for manufacturing and automation: modeling, embedded intelligence, examples of specific roadblocks
  http://www.us-robotics.us/man-proposals/7-roadmap-Henderson-Cohen-Riesenfeld.pdf

- *Robotics in Manufacturing and Automation* --- University of Nevada at Reno
  For US to be globally competitive, will need to invest in robotics technology
  http://www.us-robotics.us/man-proposals/8-proposal-Bekris.pdf

- *Robotics in Manufacturing and Automation* --- University of Massachusetts at Amherst
  Discusses GM's spending on robotics, manipulation, perception, human-robot interaction
  http://www.us-robotics.us/man-proposals/9-UMA-Brock.pdf

- *Applications of Mobile Robots in Warehouses* --- Kiva Systems, Inc.

Discusses use of 100's of robots for warehouses, needs sensors, group dynamics
http://www.us-robotics.us/man-proposals/10-NSF-Research-Panel-Wurman.pdf

- *U.S. competitiveness and funding of long-term research* --- Vanderbilt University, Universal Robotics
  Discusses U.S. competitive advantage in areas such as parallel computing and why this is important to robotics, and how to take advantage of technical leadership in these areas
  http://www.us-robotics.us/man-proposals/11-NSF-CCC-workshop-proposal-rap2-Peters.pdf

- *Reliable Computation in Manufacturing Systems* --- University of Colorado at Boulder
  Computing capabilities that can help with task planning
  http://www.us-robotics.us/man-proposals/12-CCC-Murphey.pdf

- *Metrology And Standards For Advanced Perception Systems In Intelligent Manufacturing* --- Guest Researcher, Manufacturing Engineering Lab Perception Group, NIST; Loyola College
  Discusses standards issues and metrology needs for vision systems
  http://www.us-robotics.us/man-proposals/13-CCCEastmanLoyola-Eastman.pdf

- *Robot Algorithms for Virtual Prototyping* --- University of North Carolina at Chapel Hill
  How robotic systems can better utilize CAD for designing manufacturing systems, example is for Boeing aircraft assembly
  http://www.us-robotics.us/man-proposals/14-NSF-CCC-Robotics-Manocha.pdf

- *A Model-Based Design Perspective* --- Mathworks
  Discusses safety, security and robustness requirements
  http://www.us-robotics.us/man-proposals/18-fp-Mosterman.pdf

- *Mobile Manufacturing* --- Carnegie Mellon University
  Discusses how to develop mobile robotic platforms and move away from fixed mountings
  http://www.us-robotics.us/man-proposals/17-MobileManufacturingCMUApril2008-SINGH.pdf

- *Robotics in Manufacturing & Automation* --- Corning, Inc.
  Discusses vision for integration of robots into manufacturing (rather than low value-added applications such as materials handling
  http://www.us-robotics.us/man-proposals/16-Yorio_Corning_v1.pdf

- *Robotics in Manufacturing and Automation* --- Meka Robotics
  Safe and compliant manipulators and how that fits with human-robot collaboration
  http://www.us-robotics.us/man-proposals/15-Edsinger-CCCManufacturingRoadmappingProposal_4_2008.pdf

Healthcare Robots

- *Development of Next Generation Medical Robotic Systems for Surgery, Surgical Training, and Rehabilitation* --- Case Western Reserve University
  Discusses robotic capabilities for heart bypass surgery, other surgical assistant requirements
  http://www.us-robotics.us/med-proposals/P2.pdf

- *Robot-Assisted Point of Injury Care* --- University of South Florida
  Discusses how robots could expand the scope of point of care to the point of injury, where robots are used to provide medical workers with access to previously unreachable victims (soldiers trapped by snipers and civilians trapped by a disaster or a car crash)
  http://www.us-robotics.us/med-proposals/P5.pdf

- *Space Robotics Technologies for Medicine and Healthcare* --- California Institute of Technology and Jet Propulsion Laboratories
  Discusses JPL's force-reflecting telemanipulation technology
  http://www.us-robotics.us/med-proposals/P9.pdf

- Rehabilitation, Prosthetics & Navigation --- Arizona State University
  Discusses how to use robots to assist in rehabilitation and medical therapies
  http://www.us-robotics.us/med-proposals/P13.pdf

- *Mobile Manipulation* – Willow Garage
  Technology needs for mobile manipulation (hardware standards and software platform)
  http://www.us-robotics.us/med-proposals/P19.pdf

- *Enabling Medical Robotics For The Next Generation Of Minimally Invasive Procedures* --- Carnegie Mellon University
  Discusses future design trends for medical robots
  http://www.us-robotics.us/med-proposals/P20.pdf

- *Human Movement / Safe Human Robot Interaction* --- Stanford University
  Discusses use of real-time feedback of biomechanical information to patients undergoing rehabilitation
  http://www.us-robotics.us/med-proposals/P30.pdf

- *Rehabilitation Robotics* --- Intelligent Automation, Inc.
  Discusses capabilities in intelligent robotics, electromechanical systems, signal processing, sensing and communications, distributed intelligent systems, and training technology
  http://www.us-robotics.us/med-proposals/P23.pdf

- *Therapeutic Robotics: Fundamentally Cross-Disciplinary Collaboration between Clinical Neuroscience and Robotic Engineering* --- Massachusetts Institute of Technology
  Discusses technical needs of therapeutic robotics for rehabilitation medicine
  http://www.us-robotics.us/med-proposals/P24.pdf

- *Human Tracking / Mobile Monitoring & Assistance* --- Brown University
  Develop "natural" interaction, enabling human user to maintain their situational awareness while supervising robot
  http://www.us-robotics.us/med-proposals/P25.pdf

- *Therapy Design / Rehabilitation* --- Kinetic Muscles, Inc.
  Interdisciplinary activity to translate neuroscience research results into therapy tasks
  http://www.us-robotics.us/med-proposals/P26.pdf

- *Safety, Sensors, Rehabilitation, Autism* --- SRI International
  Focuses on technologies needed for robots in the operating room and the field
  http://www.us-robotics.us/med-proposals/P29.pdf

- *Haptic Surgery, Augmented Reality and Tele Surgery* --- Immersion Corp.
  Discusses needs for new robotic haptic interface
  http://www.us-robotics.us/med-proposals/P31.pdf

- *Biomimetic Robotics Applications in Prosthetics* --- OrthoCare Innovations
  Sensor/computer integration, control system, mechanical design for rehabilitation robotics
  http://www.us-robotics.us/med-proposals/P22.pdf

- *Smart Wheelchair Systems* --- Lehigh University
  Integrating wheel chair functions with standard vehicle eliminates needs for driver/attendant
  http://www.us-robotics.us/med-proposals/P32.pdf

- *Bridging the gap between medical imaging and medical robots: Motion planning algorithms for image-guided medical procedures* --- University of Calif. Berkeley and San Francisco
  Fully integrating wealth of digital information obtained from imaging with advances in robotic hardware
  http://www.us-robotics.us/med-proposals/P33.pdf

- *Intelligent Robotic Neuroprosthetics* --- Washington University In St. Louis
  Develop robots controlled directly from neural signals, not intermediate devices (joystick)
  http://www.us-robotics.us/med-proposals/P34.pdf

- *Challenges in Robotics and Simulation for Minimally Invasive Surgery* --- formerly of University of California at San Francisco
  Discusses interface requirements for teleoperation technology
  http://www.us-robotics.us/med-proposals/P35.pdf

- *Smart Prosthetics* --- Rice University
  The use of augmented feedback (visual, haptic, auditory, multi-modal) and its ability to improve robot-mediated skill transfer and rehabilitation
  http://www.us-robotics.us/med-proposals/P38.pdf

- *Automating Surgery: Combining Imaging, Sciences Mechanical Models, and Robotics* --- Harvard School of Engineering and Applied Sciences
  Current surgical robots require the surgeon to specify every movement of the instruments; by combining 3D imaging and mechanical models, can automate much of soft tissue surgery
  http://www.us-robotics.us/med-proposals/P40.pdf

- *HRI, Human Cues and Trust* --- University of Massachusetts at Lowell
  Discusses how a user can directly select a desired object through the use of a touch screen or laser pointer, once selection is made, the arm can move autonomously to retrieve object
  http://www.us-robotics.us/med-proposals/P41.pdf

- *Telerobotics Heathcare / Assistive Therapy* --- Georgia Institute of Technology
  How robots can assist in the home activities and clinicians and healthcare professionals
  http://www.us-robotics.us/med-proposals/P42.pdf

- *Prosthetics and Rehabilitation Robotics* --- Massachusetts Institute of Technology
  Discusses needs for upper- and lower-limb prosthetics and active braces for the lower-limbs
  http://www.us-robotics.us/med-proposals/P45.pdf

- *Mobile Assistance / Safe Manipulation* --- Meka Robotics
  Discusses technology for mobility assistance of the elderly at home, at assisted living centers, and at the hospital; getting in and out of a chair, out of a bed, and walking to the toilet and all currently require assistance of a healthcare worker
  http://www.us-robotics.us/med-proposals/P43.pdf

- *The Next Challenge in Healthcare and Medical Robotics: Real-Time Physically-Based Computational Physiology* --- University of North Carolina at Chapel Hill
  Due to constraints on visibility and the complex nature of human physiology, radical advances in "physics-based computational physiology" to support training, planning, and guiding the next generation of surgical systems are needed
  http://www.us-robotics.us/med-proposals/P44.pdf

- *Robots for therapy and teaching social-cognitive skills* --- AnthroTronix, Inc.
  Interfaces, human-robot interaction, and applications for non-contact robots for physical therapy such as for stroke rehabilitation or for children with Cerebral Palsy
  http://www.us-robotics.us/med-proposals/P49.pdf

- *Simulated dissection, locomotion, musculoskeletal analysis* --- SUNY at Buffalo
  Creating and validating a Real-Time Haptic Immersive Virtual Environment (RT-HIVE) to expand, assist, train and monitor human sensorimotor skills/strengths for anatomical dissection training
  http://www.us-robotics.us/med-proposals/P50.pdf

- *Personalized Assistive Robots* --- Carnegie Mellon University
  Discusses the technical capabilities of robots as caregivers
  http://www.us-robotics.us/med-proposals/P51.pdf

- *Intelligent systems for assisted cognition and human robot interaction* --- Microsoft Research
  Discuses the need for non-invasive deployment of medical robots, devices and sensors to target emerging difficulties in the healthcare/home care space
  http://www.us-robotics.us/med-proposals/P52.pdf

- Social, assistive, and suggestive robots --- Humana, Inc.
  Requirements to develop social robots for the elderly and impaired
  http://www.us-robotics.us/med-proposals/P54.pdf

Domestic and Professional Service Robots

- *Research Roadmap for Domestic and Service Robots* --- University of California at Merced
  Discusses requirements of interfaces, learning, manipulation, etc
  http://www.us-robotics.us/service-proposals/P1.pdf

- *Roadmapping for Robotics* --- Willow Garage
  Discusses general technical needs of service robots
  http://www.us-robotics.us/service-proposals/P2.pdf

- *Domestic and Professional Service Robotics* --- Intuitive Automata, Inc.
  Discusses technical requirements for elderly home care robots and physical helper robots
  http://www.us-robotics.us/service-proposals/P3.pdf

- *Socially Guided Machine Learning* --- Georgia Institute of Technology
  Discusses technical needs for *robots with open-ended tasks in dynamic human environments*
  http://www.us-robotics.us/service-proposals/P4.pdf

- *Domestic and Professional Service Robotics* --- University of Massachusetts at Amherst
  Discusses technical needs associated with mobility and manipulation in close collaboration with a client in a residential setting
  http://www.us-robotics.us/service-proposals/P5.pdf

- *Domestic and Professional Service Robotics* --- Microsoft Research
  Identifies research requirements for hardware and mechatronic including business models for what may be completely new businesses required to allow service robotics to flourish
  http://www.us-robotics.us/service-proposals/P6.pdf

- *Domestic Service Robots To Improve Quality Of Life*--- University of North Carolina Charlotte
  Identifies technical challenges as: robot manipulation beyond grasping (i.e., sensing and perception in less structured, changing environments with uncertainty); human-robot interaction (more autonomy of the robots both in perception and in actions and less tedious low-level guidance from human operators); and multiple robot collaboration
  http://www.us-robotics.us/service-proposals/P7.pdf

- *Robust Manipulation and Sensing for Human Environments* --- Harvard/MIT Division of Health Sciences and Technology
  Discusses how the challenges associated with grasping under uncertainty can be addressed by careful mechanical design of robot hands with a focus on simplicity and robustness
  http://www.us-robotics.us/service-proposals/P8.pdf

- *Personal Robots: A Personal Computer Industry Perspective* --- Intel Research
  See personal robots as an extension of the personal computer and an opportunity to support aging in place (i.e., at home)
  http://www.us-robotics.us/service-proposals/P9.pdf

- *Towards Integrated Representations of Objects and Environments* --- George Mason Discusses adding semantic (understanding of) content to acquired sensory streams as a critical step towards enabling higher autonomy of robotic agents and better human-robot interactions
  http://www.us-robotics.us/service-proposals/P10.pdf

- *Research Roadmap for Domestic and Professional Service Robotics* --- MIT
  On integrating learning with planning so robots can plan sensing actions to improve their knowledge of the world and therefore improve execution
  http://www.us-robotics.us/service-proposals/P11.pdf

- *Engagement: A Core Competency for Domestic and Professional Service Robotics* --- Worcester Polytechnic Institute and BAE Systems Advanced Information Technology
  Discusses how to go beyond collaboration to engagement
  http://www.us-robotics.us/service-proposals/P12.pdf

- *Time Delay Domain in Bilateral Robotics* --- University of Washington
  Discusses reducing delays in various control loops to improve accuracy
  http://www.us-robotics.us/service-proposals/P13.pdf

- *A Research Roadmap for Domestic and Professional Service Robotics* --- University of Southern California, Los Angeles
  Looking at technology for *action*, *interaction*, and *engagement*
  http://www.us-robotics.us/service-proposals/P14.pdf

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