

Whitepaper on Robotics and Automation

Research Priorities for U. S. Manufacturing

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February 11, 2009

0. Executive Summary

Restructuring of U.S. manufacturing is essential to the future of economic growth, the creation of new jobs and ensuring competitiveness. This in turn requires investment in basic research, development of new technologies, and integration of the results into manufacturing systems. On 19 December 2008, the U.S. government announced \$13.4 billion in emergency federal loans to General Motors and Chrysler to facilitate restructuring and encourage new research and development – a clear example the U.S. of playing catch-up rather than taking technological leadership.

Federal Investments in research in manufacturing can revitalize American manufacturing. Investing a small portion of our national resources into a science of cost-effective, resource-efficient manufacturing would benefit American consumers and support millions of workers in this vital sector of the U.S. economy. It would allow our economy to flourish even as the ratio of workers to pensioners continuously decreases. Such a research and development program would also benefit the health care, agriculture, and transportation industries, and strengthen our national resources in defense, energy, and security. The resulting flurry of research activity would greatly improve the quality of "Made in the U.S.A." and invigorate productivity of U.S. manufacturing for the next fifty years.

Robotics is a key transformative technology that can revolutionize manufacturing. American workers no longer aspire to low-level factory jobs and the cost of U.S. workers keeps rising due to insurance and healthcare costs. Even when workers are affordable, the next generation of miniaturized, complex products with short life-cycles requires assembly adaptability, precision, and reliability beyond the skills of human workers. Improved robotics and automation in manufacturing will: a) retain intellectual property and wealth that would go off-shore without it; b) save companies by making them more competitive; c) provide jobs for developing, producing, maintaining and training robots; d) allow factories to employ human-robot teams that leverage each others' skills and strengths (e.g., human intelligence and dexterity with robot precision, strength, and repeatability), e) improve working conditions and reduce expensive medical problems; and (f) reduce manufacturing lead time for finished goods, allowing systems to be more responsive to changes in retail demand. Indeed effective use of robotics will *increase* U.S. jobs, improve the quality of these jobs, and enhance our global competitiveness.

This white paper summarizes the strategic importance of robotics and automation technologies to manufacturing industries in the U.S. economy, describes applications where robotics and automation technologies will dramatically increase productivity, and outlines a visionary research and development roadmap with key research areas for immediate investment to reach these goals.

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1. Introduction

This document summarizes the activities and results of a workshop on manufacturing and automation robotics that was supported by a grant from the Computing Community Consortium of the Computing Research Association. This workshop was the first of four organized on various areas of robotics, with the overall objective being the creation of a compelling vision for robotics research and development, and roadmaps for advancement of robotics technologies to maximize economic impact. The research agenda proposed in this report will lead to a significant strengthening of the manufacturing sector of the U.S. economy, a well-trained, technologically-astute workforce, the creation of new jobs, and broad-based prosperity for Americans.

The terms “robotics” and “automation” have a precise technical meaning. According to the Robotics and Automation Society of the Institute of Electronics and Electrical Engineers, “*Robotics* focuses on systems incorporating sensors and actuators that operate autonomously or semi-autonomously in cooperation with humans. Robotics research emphasizes intelligence and adaptability to cope with unstructured environments. *Automation* research emphasizes efficiency, productivity, quality, and reliability, focusing on systems that operate autonomously, often in structured environments over extended periods, and on the explicit structuring of such environments.”

The Manufacturing and Automation Robotics Workshop was held on June 17, 2008 in Washington DC (http://www.us-robotics.us/?page_id=9). The goal was three-fold: First, to determine the strategic importance of robotics and automation technologies in manufacturing industries in the U.S. economy (Section 2); second, to determine applications where robotics and automation technologies could increase productivity (Section 3); and third, to determine research and development that needs to be done in order to make robotics and automation technologies cost-effective in these applications (Section 4). To achieve this, whitepapers describing current uses and future needs of robotics in industry were solicited from professionals responsible for manufacturing in their companies. White papers on perceived industrial needs were solicited from academic researchers. Authors of accepted whitepapers (available at http://www.us-robotics.us/?page_id=14) were invited to attend the workshop, where authors from industry were also invited to give short presentations on present and future uses of robotics in their companies.

2. Strategic Importance of Robotics in Manufacturing

2.1 Economic Impetus

The basis for the economic growth in the last century came from industrialization, the core of which was manufacturing. The manufacturing sector represents 14% of the U.S. GDP and about 11% of the total employment [E07]. Fully 75% of the net export of the U.S. is related to manufacturing [State04], so the sector represents an area of extreme importance to the general economic health of the country. Within manufacturing, robotics represents a \$5B-industry in the U.S. that is growing steadily at 8% per year. This core robotics industry is supported by manufacturing industry that provides the instrumentation, auxiliary automation equipment, and the systems integration adding up to a \$20B industry.

The U.S. manufacturing economy has changed significantly over the last 30 years. Despite significant losses to Canada, China, Mexico and Japan over recent years, manufacturing still represents a major sector of the U.S. economy. Manufacturing, which includes the production of all goods from consumer electronics to industrial equipment, accounts for 14% of the U.S. GDP, and 11% of U.S. employment [WB06]. U.S. manufacturing productivity exceeds that of its principal trading partners. We lead all countries in productivity, both per hour and per employee [DoC04]. Our per capita productivity continues to increase with over a 100% increase over the last three decades. Indeed it is this rising productivity that keeps U.S. manufacturing competitive in the midst of recession and recovery and in the face of the amazing growth in China, India, and other emerging economies. Much of this productivity increase and efficiency can be attributed to innovations in technology and the use of technology in product design and manufacturing processes.

However, this dynamic is also changing. Ambitious foreign competitors are investing in fundamental research and education that will improve their manufacturing processes. On the other hand, the fraction of the U.S. manufacturing output that is being invested in research and development has essentially remained constant over this period. The U.S. share of total research and development funding the world has dropped significantly to only 30%. Our foreign competitors are using the same innovations in technology with, in some cases, significantly lower labor costs to undercut U.S. dominance, so U.S. manufacturing industry is facing increasing pressure. Our balance of trade in manufactured goods is dropping at an alarming \$50 billion per decade. Additionally, with our aging population, the number of workers is also decreasing rapidly and optimistic projections point to two workers per pensioner in 2050 [E07]. Robotic workers must pick up the slack from human workers to sustain the increases in productivity that are needed with a decrease in the number of human workers. Finally, dramatic advances in robotics and automation technologies are even more critical with the next generation of high-value products that rely on embedded computers, advanced sensors and microelectronics requiring micro- and nano-scale assembly, for which labor-intensive manufacturing with human workers is no longer a viable option.

In contrast to the U.S., China, South Korea, Japan, and India are investing heavily in higher education and research [NAE07]. India and China are systematically luring back their scientists and engineers after they are trained in the U.S. According to [NAE07], they are "... in essence, sending students away to gain skills and providing jobs to draw them back." This contrast in investment is evident in the specific areas related to robotics and manufacturing. Korea is investing \$100M per year for 10 years (2002-2012) into robotics research and education as part of their 21 century frontier program. The European Commission is investing \$600M into robotics and cognitive systems as part of the 7th Framework Programme. While smaller in comparison to the commitments of Korea and the European Commission, Japan is investing \$350M over the next 10 years in humanoid robotics, service robotics, and intelligent environments. The non-defense U.S. federal investment is small by most measures compared to these investments.

2.2 Growth Areas

The Department of Commerce and the Council on Competitiveness [CoC08, DoC04] have analyzed a broad set of 280 companies as to their consolidated annual growth rates. The data categorized for major industrial sectors is shown in the table below.

Sector	Average Growth	Growth
Robotics – manufacturing, service and medical	20%	0-120%
IP Companies	21%	15-26%
Healthcare/eldercare	62%	6-542%
Entertainment/toys	6%	4-17%
Media / Games	14%	2-36%
Home appliances	1%	-4-7%
Capital equipment	8%	-4-20%
Automotive	0%	-11-13%
Logistics	21%	4-96%
Automation	4%	2-8%

Consolidated annual growth rates over a set of 280 U.S. companies for the period 2004-2007.

Current growth areas for manufacturing include logistic including material handling, and robotics. Given the importance of manufacturing in general, it is essential to consider how technology such as robotics can be leveraged to strengthen U.S. manufacturing industry.

2.3 A Vision for Manufacturing

U.S. manufacturing today is where database technology was in the early 1960's, a patchwork of ad hoc solutions that lacked the rigorous methodology that leads to scientific innovation. In 1970 when Ted Codd, an IBM mathematician, invented relational algebra, an elegant mathematical database model that galvanized federally funded research and education leading to today's \$14 billion database industry. Manufacturing would benefit enormously if analogous models could be developed. Just as the method to add two numbers together doesn't depend on what kind of pencil you use, manufacturing abstractions might be wholly independent of the product one is making or the assembly line systems used to assemble it.

Another precedent is the Turing Machine, an elegant abstract model invented by Alan Turing in the 1930s, which established the mathematical and scientific foundations for our now-successful high-tech industries. An analogy to the Turing Machine for design, automation and manufacturing, could produce tremendous payoffs. Recent developments in computing and information science now make it possible to model and reason about physical manufacturing processes, setting the stage for researchers to "put the *Turing* into Manufac*Turing*". The result, as with databases and computers, would be higher quality, more reliable products, reduced costs, and faster delivery [GK07].

More effective use of robotics, through improved robotics technologies and a well-trained workforce, will *increase* U.S. jobs and global competitiveness. Traditional assembly-line workers are nearing retirement age. American workers are currently not well-trained to work with robotic technologies and the costs of insurance and healthcare continue to rise. Even when workers are affordable, the next

generation of miniaturized, complex products with short life-cycles requires assembly adaptability, precision, and reliability beyond the skills of human workers. Widespread deployment of improved robotics and automation in manufacturing will: (a) retain intellectual property and wealth that would go off-shore without it, (b) save companies by making them more competitive, (c) provide jobs for maintaining and training robots, (d) allow factories to employ human-robot teams that safely leverage each others' strengths (e.g., human are better at dealing with unexpected events to keep production lines running, while robots have better precision and repeatability, and can lift heavy parts), (e) reduce expensive medical problems, e.g., carpal tunnel syndrome, back injuries, burns, and inhalation of noxious gases and vapors, and (f) reduce time in pipeline for finished goods, allowing systems to be more responsive to changes in retail demand.

Investments in research and education in manufacturing can revitalize American manufacturing. Investing a small portion of our national resources into a science of cost-effective, resource-efficient manufacturing would benefit American consumers and support millions of workers in this vital sector of the U.S. economy. Such investments would benefit health care, agriculture, and transportation, and strengthen our national resources in defense, energy, and security. The resulting flurry of research activity would invigorate the quality and productivity of "Made in the U.S.A." for the next fifty years.

3. Research Roadmap

3.1 The Process

The manufacturing technology roadmap describes a vision for the development of *critical capabilities* for manufacturing by developing a suite of basic *technologies* in robotics. Each critical capability stems from one or more important broad *application domains* within manufacturing. These point to the major technology areas for basic research and development (as shown in Figure 1 and discussed in Section 4). Integration of all the parts of this roadmap into a cohesive program is essential to create the desired revitalization of manufacturing in the U.S.

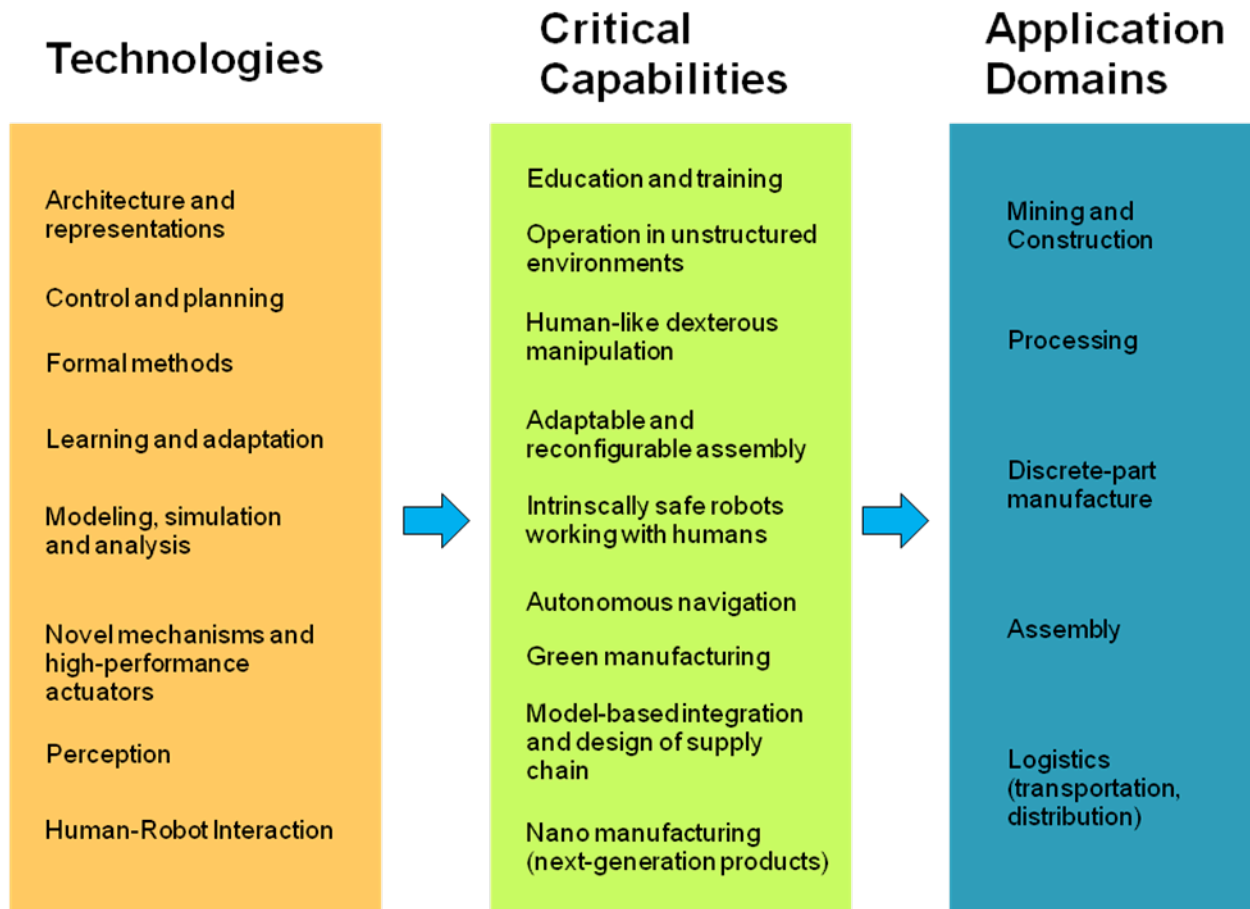


Figure 1: The roadmap process: Research and development is needed in technology areas that arise from the critical capabilities required to impact manufacturing application domains.

3.2 Robotics and Manufacturing Vignettes

We briefly discuss the motivating applications with vignettes and the critical capabilities required for a dramatic positive impact on the applications. The vignettes serve to illustrate paradigm changes in manufacturing and as examples of integration across capability and technology areas. The roadmap articulates five, ten and fifteen year milestones for the critical capabilities.

Vignette 1: Assembly Line Assistant Robots

An automotive manufacturer experiences a surge in orders for its new electric car design and needs to quickly merge its production capability with other earlier models already in production. Assembly tasks are rapidly reallocated to accommodate the new more efficient car model. A set of assembly line assistant robots are brought in and quickly configured to work alongside the retrained human workers on the new tasks. One practice-shift is arranged for the robot's sensor systems and robot learning algorithms to fine-tune parameters, and then the second shift is put into operation, doubling plant output in four days. Then, a change by a key supplier requires that the assembly sequence be modified to accommodate a new tolerance in the battery pack assembly. Engineers

use computational tools to quickly modify the assembly sequence: then they print new instructions for workers and upload modified assembly programs to the assistant robots.

Vignette 2: One-of-a-kind discrete-part manufacture and assembly

A small job shop with 5 employees primarily catering to orders from medical devices companies is approached by an occupational therapist one morning to create a customized head-controlled input device for a quadriplegic wheelchair user. Today the production of such one-of-a-kind devices would be prohibitively expensive because of the time and labor required for setting up machines and for assembly. The job shop owner reprograms a robot using voice commands and gestures, teaching the robot when it gets stuck. The robot is able to get the stock to mills and lathes, and runs the machines. While the machines are running, the robot sets up the necessary mechanical and electronic components asking for assistance when there is ambiguity in the instruction set. While moving from station to station, the robot is able to clean up a coolant spill and alert a human to safety concerns with a work cell. The robot responds to a request for a quick errand for the shop foreman in between jobs, but is able to say no to another request that would have resulted in a delay in its primary job. The robot assembles the components and the joystick is ready for pick-up by early afternoon. This happens with minimal interruption to the job shop's schedule.

Vignette 3: Rapid, integrated model-based design of the supply chain

The packaging for infant formula from a major supplier from a foreign country is found to suffer from serious quality control problems. The US-based lead engineer is able to use a comprehensive multi-scale, discrete and continuous model of the entire supply chain, introduce new vendors and suppliers, repurpose parts of the supply chain and effect a complete transformation of the chain of events: production, distribution, case packing, supply and distribution. An important aspect of the transformation is the introduction of 20 robots to rapidly manufacture the redesigned package

These vignettes may seem far-fetched today, but we have the technology base, the collective expertise, and the educational infrastructure to develop the broad capabilities to realize this vision in 15 years with appropriate investments in the critical technology areas.

3.3 Critical Capabilities for Manufacturing

In this section, we briefly discuss the critical capabilities and give examples of possible 5, 10, and 15 year milestones. After this, in Section 4 we describe some promising research directions that could enable us to meet these milestones.

Adaptable and reconfigurable assembly

Today the time lag between the conceptual design of a new product and production on an assembly line in the U.S. is unacceptably high. For a new car, this lead-time can be as high as twenty four months. Given a new product and a set of assembly line subsystems that can be used to make the product, we want to achieve the ability to adapt the subsystems, reconfigure them and set up workcells to produce

the product. Accordingly the roadmap for adaptable and reconfigurable assembly includes the following goals over the next fifteen years.

- 5 years: Achieve ability to set up, configure and program basic assembly line operations for new products with a specified industrial robot arm, tooling and auxiliary material handling devices in under 24 hours.
- 10 years: Achieve ability to set up, configure and program basic assembly line operations for new products with a specified industrial robot arm, tooling and auxiliary material handling devices in one 8 hour shift.
- 15 years: Achieve ability to set up, configure and program basic assembly line operations for new products with a specified industrial robot arm, tooling and auxiliary material handling devices in one hour.

Autonomous navigation

Autonomous navigation is a basic capability that will impact the automation of mining and construction equipment, the efficient transportation of raw materials to processing plants, automated guided vehicles for material handling in assembly lines, and logistics support operations like warehousing and distribution. Enabling safe autonomous navigation in unstructured environments with static obstacles, human-driven vehicles, pedestrians and animals will require significant investments in component technologies. The roadmap for autonomous navigation consists of the following milestones.

- 5 year: Autonomous vehicles will be capable of driving in any modern town or city with clearly lit and marked roads and demonstrate safe driving comparable to a human driver. Performance of autonomous vehicles will be superior to that exhibited by human drivers in such tasks as navigating through an industrial mining area or construction zone, backing into a loading dock, parallel parking, and emergency braking and stopping.
- 10 years: Autonomous vehicles will be capable of driving in any city and on unpaved roads, and exhibit limited capability for off-road environment that humans can drive in, and will be as safe as the average human driven car.
- 15 years: Autonomous vehicles will be capable of driving in any environment in which humans can drive. Their driving skill will be indistinguishable from humans except that robot drivers will be safer and more predictable than a human driver with less than one year's driving experience.

Green manufacturing

As American architect William McDonough said, "pollution is a symbol of design [and manufacturing] failure." Our current approach to manufacturing in which components and then sub-systems are integrated to meet top-down specifications has to be completely rethought to enable green manufacturing. Today's solutions to reduce manufacturing waste mostly target process waste, utility waste and waste from shutdowns and maintenance. Our roadmap for green manufacturing emphasizes the recycling of all the components and subsystems used *throughout* the manufacturing process, starting from mining and processing of raw materials to production and distribution of finished products. We are particularly concerned with re-use of the manufacturing infrastructure, recycling of

raw materials, minimizing the energy and power requirements at each step and repurposing subsystems for the production of new products.

- 5 years: The manufacturing process will recycle 10% of raw materials, reuse 50% of the equipment, and use only 90% of the energy used in 2010 for the same process.
- 10 years: The manufacturing process will recycle 25% of raw materials, reuse 75% of the equipment, and use only 50% of the energy used in 2010 for the same process.
- 15 years: The manufacturing process will recycle 75% of raw materials, reuse 90% of the equipment, and use only 10% of the energy used in 2010 for the same process.

Human-like dexterous manipulation

Robot arms and hands will eventually out-perform human hands. This is already true in terms of speed and strength. However, human hands still out-perform their robotic counterparts in tasks requiring dexterous manipulation. This is due to gaps in key technology areas, especially perception, robust high-fidelity sensing, and planning and control. The roadmap for human-like dexterous manipulation consists of the following milestones.

- 5 years: Low-complexity hands with small numbers of independent joints will be capable of robust whole-hand grasp acquisition.
- 10 years: Medium-complexity hands with tens of independent joints and novel mechanisms and actuators will be capable of whole-hand grasp acquisition and limited dexterous manipulation.
- 15 years: High-complexity hands with tactile array densities approaching that of humans and with superior dynamic performance will be capable of robust whole-hand grasp acquisition and dexterous manipulation of objects found in manufacturing environments used by human workers.

Model-based integration and design of supply chain

Recent developments in computing and information science have now made it possible to model and reason about physical manufacturing processes, setting the stage for researchers to "put the *Turing* into *ManufacTuring*". If achieved, as with databases and computers, would enable interoperability of components and subsystems and higher quality, more reliable products, reduced costs, and faster delivery. Accordingly our roadmap should include achievements that demonstrate the following milestones.

- 5 years: Safe, provably-correct designs for discrete part manufacturing and assembly so bugs are not created during the construction of the manufacturing facility.
- 10 years: Safe, provably-correct designs for the complete manufacturing supply chain across multiple time and length scales so bugs are not created during the design of the manufacturing supply chain.
- 15 years: Manufacturing for Next Generation Products: With advances in micro and nano-scale science and technology, and new processes for fabrication, we will be able to develop safe, provably-correct designs for any product line.

Nano-manufacturing

Classical CMOS-based integrated circuits and computing paradigms are being supplemented by new nano-fabricated computing substrates. We are seeing the growth of non-silicon micro-system technologies and novel approaches to fabrication of structures using synthetic techniques seen in nature. Advances in MEMS, low-power VLSI, and nano-technology are already enabling sub-mm self-powered robots. New parallel, and even stochastic, assembly technologies for low-cost production are likely to emerge. Many conventional paradigms for manufacturing will be replaced by new, yet-to-be-imagined approaches to nano-manufacturing. Accordingly the roadmap for nano-manufacturing and nano-robotics must emphasize basic research and development as follows.

- 5 years: Technologies for massively parallel assembly via self-assembly and harnessing biology to develop novel approaches for manufacturing with organic materials.
- 10 years: Manufacturing for the post-CMOS revolution enabling the next generation of molecular electronics and organic computers
- 15 years: Nano-manufacturing for nano-robots for drug delivery, therapeutics and diagnostics.

Perception for unstructured environments

Automation in manufacturing has proven to be simpler for mass production with fixed automation, and the promise of flexible automation and automation for mass customization has not been realized except for special cases. One of the main reasons is that fixed automation lends itself to very structured environments in which the challenges for creating “smart” manufacturing machines are greatly simplified. Automation for small lot sizes necessitate robots to be smarter, more flexible, and able to operate safely in less structured environments shared with human workers. In product flow layouts for example, robots and other machines go to various operation sites on the product (e.g., an airplane or a ship) to perform their tasks, whereas in a functional layout, the product travels to various machines. The challenges of one-of-a-kind manufacturing exacerbate these difficulties. The roadmap for perception includes the following milestones.

- 5 years: 3-D perception enabling automation even in unstructured typical of a job shop engaged in batch manufacturing operations
- 10 years: Perception in support of automation of small lot sizes, for example, specialized medical aids, frames for wheelchairs, and wearable aids.
- 15 years: Perception for truly one-of-a-kind manufacturing including customized assistive devices, personalized furniture, specialized surface and underwater vessels, and spacecrafts for planetary exploration and colonization.

Intrinsically safe robots working with humans

Robotics has made significant progress toward enabling full autonomy and shared autonomy in tasks such as driving vehicles, human physical therapy, and carrying heavy parts (using cobots). Leveraging these advances to enable autonomy and shared autonomy in other tasks such as assembly and manipulation poses a significant challenge. Automotive industry experts recognize the benefits of automation support for human workers either in the form of humanoid assistants or smart machines

that safely interact with human workers. To define research milestones we propose three levels of assembly line ability:

1. Level I Ability: humans require no special skills and < 1 hour of training. examples: pick and place, insertion, packing. A canonical benchmark that can be used for testing and comparison between groups might be generic tasks such as threading and unthreading a standard 1" nut and bolt.
2. Level II Ability: humans require minor skills and 1-10 hours of training. examples: cutting / shaping, soldering, riveting. A canonical benchmark might be disassembling and reassembling a specific standard flashlight.
3. Level III Ability: humans require skill and > 10 hours of training. examples: specified standard welding, machining, inspecting benchmarks.

The roadmap for robots working with humans is as follows.

- 5 years: Demonstrate a prototype assembly-line robot with sensors that can detect and respond to human gestures and movement into its workspace while consistently performing at Level I ability (see above) alongside a human for 8 hours without requiring any intervention from the people nearby.
- 10 years: Demonstrate a prototype assembly-line robot with sensors that can detect and respond to human gestures and movement into its workspace while consistently performing at Level II ability alongside a human for 40 hours without requiring any intervention from the people nearby.
- 15 years: Demonstrate a commercially available assembly-line robot with sensors that can detect and respond to human gestures and movement into its workspace while consistently performing at Level III ability alongside a human for 80 hours without requiring any intervention from the people nearby.

Education and Training

The U.S. can only take advantage of new research results and technology if there is workforce well-trained in the basics of robotics and the relevant technologies. This workforce should have a wide range of skill and knowledge levels – from people trained at vocational schools and community colleges to operate high-tech manufacturing equipment, to BS- and MS-level developers trained to create robust high-tech manufacturing equipment, to PhD-level basic researchers trained to develop and prove new theories, models and algorithms for next-generation robots. To train the best workforce, the educational opportunities must be broadly available. The roadmap for the workforce is as follows.

- 5 years: Each public secondary school in the U.S. has a robotics program available after school. The program includes various informational and competitive public events during each session, and participants receive recognition comparable to other popular extra-curricular activities.
- 10 years: In addition to the 5-year goal, every 4-yr college and university offers concentrations in robotics to augment many Bachelors, Masters, and PhD degrees.
- 15 years: The number of domestic graduate students at all levels with training in robotics is double what it is in 2008. Ten ABET-approved BS programs in Robotics and 10 PhD programs in Robotics are active.

4. Research and Development: Promising Directions

Achieving the *critical capabilities* described in Section 3 above and listed in the center column of Figure 1 requires basic research and development of the *technologies* listed in the left column of Figure 1. These technologies are briefly motivated and described below along with promising research directions. Note that each one supports more than one critical capability. For example, the “Perception” technology directly impacts “Operation in unstructured environments,” “Intrinsically safe robots working with humans,” “Autonomous navigation,” and “Human-like dexterous manipulation.”

4.1 Learning and adaptation

One of the biggest barriers to the use of robots in factories is the high cost of engineering the workcells, i.e., the design, fabrication, and installation of jigs, fixtures, conveyors, and third-party sensors and software. These engineering costs are typically several times the cost of the primary robotic hardware. Robots must be able to perform their tasks in environments with greater uncertainty than current systems can tolerate. One possible way to achieve this is through learning by demonstration. In this case, a human performs the task several times without the engineered environment while the robot observes. The robot then learns to mimic the human by repeatedly performing the same task safely and comparing its actions and task results to the human’s. Robots could also adapt by monitoring their actions, comparing them to nominal parameterized task representations, and adjusting the parameters to optimize their performance.

4.2 Modeling, analysis, simulation, and control

Modeling, analysis, simulation, and control are essential to understanding complex systems, such as manufacturing systems. Future manufacturing systems will require models of parts or subassemblies undergoing intermittent contact, flexible sheet-like materials, linkages with closed chains, systems with changing kinematic topologies, and relevant physics at the micro- and nano-scales. To leverage these to design improved manufacturing systems, models and the resulting simulation techniques need to be validated experimentally and combined with search and optimization techniques. With improved models and simulation techniques and with improved high-performance computing, we will have the ability to simulate all aspects of manufacturing systems from the extraction of raw materials, to the production of parts, to the assembly and testing

4.3 Formal methods

In some domains, mathematical models and the tools of logic have been used to guide specification, development, and verification of software and hardware systems. Because of the high cost of application, these *formal methods* have been used in significant manufacturing efforts primarily when system integrity is of the utmost importance, such as spacecraft and commercial aircraft. However, it is not only the cost that prevents formal methods from common use in the development of manufacturing (and many other engineered) systems. Lack of use is also related to the limitations of the framework for

representing important manufacturing operations, such as the assembly of parts, which can be viewed as hybrid systems with disjunctive nonlinear inequality constraints of many continuous variables.

4.4 Control and planning

Robots of the future will need more advanced control and planning algorithms capable of dealing with systems with greater uncertainty, wider tolerances, and larger numbers of degrees of freedom than current systems can handle. We will likely need robot arms on mobile bases whose end-effectors can be positioned accurately enough to perform fine manipulation tasks despite the base not being rigidly anchored to the floor. These robots might have a total of 12 degrees of freedom. At the other extreme are anthropomorphic humanoid robots that could have as many 60 degrees of freedom. Powerful new planning methods, possibly combining new techniques from mathematical topology and recent sampling-based planning methods may be able to effectively search the relevant high-dimensional spaces.

4.5 Perception

Future factory robots will need much improved perception systems in order to monitor the progress of their tasks, and the tasks of those around them. Beyond task monitoring, the robots should be able to inspect subassemblies and product components in real time to avoid wasting time and money on products with out-of-spec parts. They should also be able to estimate the emotional and physical state of humans, since this information is needed to maintain maximal productivity. To do this we need better tactile and force sensors and better methods of image understanding. Important challenges include non-invasive biometric sensors and useable models of human behavior and emotion.

The large cost of engineering of workcells derives mostly from the need to reduce uncertainty. To remove this cost, the robots must be capable of removing uncertainty through high-fidelity sensors or actions that reduce uncertainty. Sensors must be able to construct geometric and physical models of parts critical to an assembly task and to track the progress of the task. If this task is being done partly or wholly by a human, then non-invasive biometric sensors must also determine the state of the human. Grasping actions and assembly strategies that previously depended on expensive tooling should be redesigned so that they take advantage of compliance to remove uncertainty.

4.6 Novel mechanisms and high-performance actuators

Improved mechanism and actuators will generally lead to robots with improved performance, so fundamental research is needed on these topics. However, as robotics is applied to applications in novel domains such the manipulation of parts on the nano-and micro-scales, materials-sensitive environments such as those surrounding MRI scanners, and environments shared with humans, the designs (including material choices) of actuators and mechanisms will have to be rethought. New mechanisms for human augmentation include exoskeletons, smart prosthetics, and passive devices. These systems will require high strength-to-weight ratios, actuators with low emissions (including noise and electromagnetic), and natural interfaces between the human and the mechanisms.

4.7 Human-robot interaction

Robots in future factories will be in physical contact with humans and other robots, if not directly, then through an object being grasped by both simultaneously. Inadvertent contact may also occur. When robots are collaborating with humans, they must be able to recognize the human activities to maintain proper task synchrony. Finally, robots must be able to communicate with humans in multiple ways; verbally and non-verbally, and must be easy to train. These situations suggest the need for new sensing systems with higher bandwidths and resolutions than those available today, the use of sensing systems that capture biometric data of human workers that has previously been ignored in robot control, and the design of intrinsically safe robots with fail-safe operating systems and tools to verify the safety and correctness of robot programs.

4.8 Architecture and representations

New manufacturing robots must be intelligent enough to productively share space with humans and other robots and to learn how to improve their effectiveness with experience. To support such learning, robot operating systems, and the models and algorithms behind them, must be sufficiently expressive and properly structured. They will need ways to represent the various manipulation skills and relevant physical properties of the environment to incorporate their impact on task execution. There should be continuous low-level perception-action loops whose couplings are controlled by high-level reasoning. Robots will exploit flexible and rich skill representations in conjunction with observation of humans and other robots to learn new skills autonomously. Robots will need new methods of representing environmental uncertainties and monitoring tasks that facilitate error recovery and skill enhancement based on these errors.

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6. Contributors

This report has its origins in presentations and discussions at a workshop on manufacturing and automation robotics that took place June 17, 2008 in Washington, DC. The report is part of the CCC study on Robotics. The Computing Community Consortium (CCC) is a project managed by the Computing Research Association (CRA) and is sponsored by the National Science Foundation (NSF). The present report has been authored by the workshop organizers and does not necessarily reflect the opinion of CRA, CCC or NSF. The responsibility of the report lies entirely with the authors.

The workshop organizers were Henrik I Christensen, Ken Goldberg, Vijay Kumar, and Jeff Trinkle. The workshop had broad participation across academia and industry as shown in the list of participants below:

Tom Batzinger	GE
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Karl Bohringer	UW
Joe Bordogna	UPenn
Gary Bradski	Willow Garage
Oliver Brock	UMass
Jeff Burnstein	RIA
Thomas Fuhlbrigge	ABB, Inc
Henrik I Christensen	Georgia Tech
Roger Eastman	Loyola
Aaron Edsinger	Meka
Erica Fuchs	CMU
Ken Goldberg	UC Berkeley
Tom Henderson	Utah
William Joyner	Semiconductor Research Corporation
Lydia Kavasaki	URice
Clint Kelly	Georgia Tech (former SAIC)
Alonzo Kelly	CMU
Vijay Kumar	UPenn
Dinesh Manocha	UNC
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Pieter Mosterman	Mathworks
Elena Messina	NIST
Todd Murphey	Colorado
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Stuart Shephard	KUKA
Sanjiv Singh	CMU

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