EL Program: Next-Generation Robotics and Automation

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Strategic Goal: Smart Manufacturing, Construction, and Cyber-Physical Systems

Summary:
This program addresses the measurement science and standards necessary to enable the next generation of robots and automation systems and to ensure their adoption in manufacturing in the U.S. The program addresses major barriers including perception, manipulation, mobility, autonomy, and safety. It does so through targeted projects that develop standards and performance measures that will help spur development and applications of intelligent robots that safely operate in close proximity to people. The targeted manufacturers include both large manufacturers and the small and medium-sized enterprises that comprise 86% of all manufacturing establishments, but often lag in adopting new technologies.

Next-Generation Robotics and Automation
Smart Manufacturing, Construction, and Cyber-Physical Systems

Objective: To develop and deploy advances in measurement science to safely increase the versatility, autonomy, and rapid re-tasking of intelligent robots and automation technologies for smart manufacturing and cyber-physical systems applications by 2016.

What is the problem? The U.S. needs to retain its leadership position in manufacturing, which is being whittled away by cheap labor and growing sophistication of foreign competitors[1]. In order to remain competitive, new ways must be found to make products faster, better, and cheaper. Perhaps the most promising approach comes from the new generation of robotics and automation[2]. The Office of Science and Technology Policy (OSTP) and Office of Management and Budget (OMB) have called for agencies to prioritize "those programs that advance the state of the art in manufacturing, with particular emphasis on government-industry-university partnerships and enabling technologies (such as robotics, materials development, and additive manufacturing) that benefit multiple sectors."[3]

According to a major research roadmap published by the Computing Community Consortium (CCC) based on a study funded by NSF[4], robotics "clearly represents one of the few technologies capable in the near term of building new companies and creating new jobs." The roadmap report concludes that "robotics technology holds the potential to transform the future of the country and is likely to become as ubiquitous over the next few decades as computing technology today." The President's Framework for Revitalizing American Manufacturing recognizes the importance of "developing advanced robotics technologies that allow the U.S. to retain manufacturing and respond rapidly to new products and changes in consumer demand".[5] However, the development and deployment of advanced robotics technologies is hindered by a lack of measurement science for quantitatively specifying the required performance in the following key technology areas ,as well as objectively and reproducibly measuring how well robots and automation systems meet the requirements.[6]

- **Safety** systems to allow safe operation in proximity to humans;
- **Perception** systems to robustly identify and locate people, parts, and equipment in the robot's environment;
- **Manipulation** technologies to grasp and manipulate a wide range of parts without requiring custom grippers and fixtures;
- **Mobility** systems to autonomously navigate dynamic manufacturing environments;
- **Autonomy** capabilities to plan and execute tasks without painstaking programming of all steps.

The lack of measurement science increases the risk of adoption of robots by industry, especially small and medium enterprises, due to the lack of means to predict or ensure successful deployment and discourages more widespread use of this promising technology for US manufacturers.

Why is it hard to solve? Addressing this problem is difficult because next generation robots are complex systems, integrating safety, perception, manipulation, mobility, and autonomous planning subsystems that are themselves complex. The measurement science challenges and complexities within these areas include the following:

- **Safety:** must assess with high confidence the ability of new sensor and software-based systems to reliably achieve an equivalent level of safety to today's gate and fence-based approaches;
- **Perception:** must be able to characterize the ability of sensors to reliably track and predict complex motions of people and equipment in the workspace, and to identify and locate parts of different shapes, sizes, colors, and reflectivities in cluttered environments with uncontrolled, changing ambient lighting;
- **Manipulation:** must characterize the grasping ability of grippers with respect to force control, compliance, graspable part geometries, friction coefficients, and other factors;
- **Mobility:** must be able to validate the ability of vehicles to move safely in dynamic unstructured environments, while detecting and avoiding a wide variety of obstacles;
- **Autonomy:** must be able to assess the ability of the robot control system to plan, execute, and adapt its movements based on knowledge of how to perform a task, combined with sensed information.

How is it solved today, and by whom? Today's solution is "a patchwork of ad hoc solutions that lacked the rigorous methodology that leads to scientific innovation."[7] Each of the disciplines required for robotics and automation systems – perception, manipulation, mobility, and autonomous planning – has developed largely independently, mostly focused on non-manufacturing applications, and few organizations have people with skills in all the necessary technologies. This has led to a segmentation of the industry, where integrators custom-build robotic work cells, frequently continuing to manage the applications over their lifetimes, reprogramming whenever the part or task changes. The cost of installation and supporting infrastructure in a cell is normally up to ten times the cost of the robot.[8] This is only cost-effective for large manufacturers who will use a particular work cell for a considerable length of time.

Robots have penetrated only a small segment of the manufacturing domain.[9] Further penetration within manufacturing is limited by cost-prohibitive infrastructure required for robot installation. 90% of industrial robots today lack any ability to sense their external environment[10]. "Industrial robots still do not have the sensing, control and decision making capability that is required to operate in unstructured, 3D environments."[11] This means that the world in which they function must be perfectly structured to match the pre-programmed instructions that the robots blindly execute.

The need for more flexible and easy-to-use robots has been recognized to a much greater extent outside the U.S.[12]. The European Commission spent ~$750 M in 2007-2012 for cognitive and robotics related research[13], much of it for manufacturing. Japan spends similar amounts.

Why NIST? The program directly supports the Engineering Laboratory's mission to anticipate and meet the measurement science and standards needs of U.S. industries conducting technology-intensive manufacturing. It is aligned with the Laboratory's goal to enable the next generation of innovative and competitive manufacturing, construction, and cyber-physical systems through advances in measurement science, and addresses the core competence "Intelligent sensing, control, processes, and automation for cyber-physical systems".

Progress in robotics is currently hindered by the lack of a common language and tools to specify quantitatively the performance that is needed and objectively and reproducibly measure how well systems meet the performance requirements.[14,15] Lack of benchmarks and hardware and software platform standards impedes collaborative progress within the research community, makes it difficult to assess experimental results, and leads to duplication of effort. This program applies NIST's measurement science expertise together with its robotics expertise, to ensure that U.S. industries successfully leverage the huge potential of robotics. NIST is uniquely positioned to foster collaboration between users, robot manufacturers, and academics to identify common robotics measurement science needs, develop standard test methods to address them, and encourage end-user adoption. NIST is actively involved in safety standards for robots[16], so has the necessary contacts and exposure to manufacturers, integrators and users that will allow successful transfer of knowledge to industry.

What is the new technical idea? The key idea is to develop and apply the measurement science that is currently lacking in the areas of safety, perception, manipulation, mobility, and autonomy to isolate and measure robot performance against specific *industry* requirements. An industry requirements-driven measurement portfolio will establish a common language between the researchers who are advancing robotic technologies and the end users and systems integrators who design and implement the robotic work cells. With a common means of expressing of what is required by end users and characterizing the performance of a robot system and its components, advances in robotic technologies can be focused in the necessary directions and the risk of their integration on factory floors – especially for small companies – can be reduced. The program will take an integrated approach to provide solution-enabling deliverables in each of the five technology areas:

- **Safety:** measurement science for assessing systems that monitor and control robot motions near people and limit power and forces exerted in the case of human-robot contact;
- **Perception:** measurement science for the performance of sensors that can identify manufacturing parts and tools and compute their positions and orientations, reducing the need for expensive fixturing;
- **Manipulation:** measurement science for gripper performance for part grasping tasks in bin-picking and other assembly operations to reduce the need for trial-and-error development of custom manipulators;

- **Mobility:** measurement science for safety and performance of mobile robots that operate near people and for autonomous navigation that will reduce the need for fixed paths and guidance markers;
- **Autonomy:** measurement science for data representations and for the performance of planning systems that will result in easier programming in less structured environments.

Why can we succeed now? The time is right because of the increased recognition by both manufacturers and government that robotics will become a driving force in industry and society and it is crucial for the United States to recapture and retain the innovation leadership in this growing enterprise.[17,18]

It is also the right time because several necessary enabling technologies and tools are becoming mature or cost-effective enough to become incorporated into robotic systems to address the above-mentioned gaps. For instance, computational power is becoming affordable and powerful enough to support the type of processing and decision-making required for robots to become adaptive to their environments. New methods of reasoning are making autonomy and rapid re-tasking more feasible, and a new generation of sensors that provides three-dimensional information about the robot's surroundings is becoming mature enough to address the requirement that "perception systems for automation in dynamic environments will need to be comprehensive, pervasive, and redundant."[19] New robotic grippers with more flexibility and force feedback are appearing on the market. Advances in the defense robotics domain have enabled robots to perceive and navigate within complex and unpredictable environments. The sensors and algorithms from the defense domain can be harvested for industrial and other applications, but they are not directly transferable.

What is the research plan? NIST will work closely with the manufacturing user communities to capture their needs and requirements for robotics and coordinate with organizations that will create the next generation of robotics to meet the needs of manufacturing. This program will elicit detailed performance requirements from manufacturers (large, medium, and small), develop preliminary test methods to measure robot performance against requirements, and iterate with the end-user and technology provider communities to assess and refine the metrics and measurement techniques and implement standards. NIST will use bin picking[20] as an exemplar manufacturing challenge to unify the projects within the Program. Achieving successful robotic bin picking will require advancements that are generalizable to assembly and pick-and-place operations. Integrated projects in five key thrust areas will address the advances needed for successful robotic bin picking and other industrial applications:

- **Safe Human-Robot Interaction:** Progress towards the goal of fully collaborative human-robot teams will be achieved in stages through two projects. One project will address allowing humans and robots to work within a restricted shared workspace. Metrics and measurement methods will be developed for the safety system's ability to detect people in the vicinity of the robot and slow it down or stop it adaptively and ensure that the forces and pressures exerted by the robot in contact with humans do not result in injury. The second project will address the technical foundations for performance measures and standards for safety systems that identify humans, track their motions, and predict their actions, so that the robot may avoid collisions with them. It will also address safe operation of robot arms mounted on mobile bases.
- **Sensing and Perception for Manufacturing Applications**: Two projects develop the measurement science foundations for evaluating the performance of and characterizing sensor

systems through experimentation in a well-calibrated testbed. The projects also research the sources of uncertainty and how they contribute to the overall perception system uncertainty. The projects will concentrate respectively on technical foundations to enable standards for (1) systems that identify and locate parts, particularly for assembly tasks, and (2) systems that identify and locate moving objects and humans.

- **Manipulation for Manufacturing Applications**: A project in dexterous manipulation addresses measurement science for manipulators that are more capable than the current custom-built and task-specific grippers. The project will develop metrics, artifacts, and methods to measure the characteristics of grippers and robotic hands that allow them to manipulate parts, such as grip stability, surface cohesion, and obstruction stability. Both macro and micro-scale manipulation are covered.
- **Mobility for Manufacturing Applications**: One project in the Program experimentally develops performance metrics and test methods to enable standards for safety of industrial vehicles to expand their use near people. These include determining the amount of force a vehicle can safely exert on humans and measuring vehicles' ability to detect and avoid obstacles.
- **Autonomy for Manufacturing Applications**: Autonomy encompasses all the computation and analysis of the state of the world that enables a system to behave intelligently. The Program includes a project that is helping to develop knowledge representation and planning methods for part handling that enable rapid re-tasking. This will lead to standard representations and performance metrics to evaluate the ability of a planner to plan a new task and adapt to changes in the world.

How will teamwork be ensured? The projects are all carried out within the Intelligent Systems Division, although staff members are drawn from all groups within the Division. Most staff will work on multiple projects, and projects have specific ties where one project depends on another for data, capabilities, or expertise. The projects will be unified under common testbeds and exemplar industrial scenarios representing uses of advanced robotic capabilities. The projects will hold regular project meetings and the program managers will hold periodic meetings with project leaders to ensure consistency and collaboration between projects.

What is the impact if successful? U.S. industries will attain greater responsiveness, productivity, and higher quality through more widespread adoption of robotics and automation with less risk through the innovations stimulated, guided, and validated by the performance metrics, test methods, and standards developed in this program. This will allow the U.S. to effectively compete in the global market. Once robots are more flexible, reliable, safer, and easier to install and interface, their applicability and use will increase tremendously, enabling many more manufacturers, especially SMEs, to reap their benefits:

- Robots that can be trusted to work alongside and assist humans will reduce injuries due to repetitive motions and strains as they offload the heavy and tedious work from humans without needing special barriers and restricted areas. This impact will result from the Safe Human-Robot Interaction thrust.
- Sensing of part positions will relieve the need for robot calibration, part fixturing and painstaking programming of robot motions, and will be achieved through the Sensing and Perception for Manufacturing Applications thrust.

- Dexterous grippers will reduce the need for customized end-tooling and careful grasp programming, allowing manufacturers to apply robots to a broader set of tasks than is currently possible today. This will be addressed in the thrust on Manipulation for Manufacturing Applications.
- Mobile robot navigation will enable safe automated material handling in small and medium manufacturing operations without expensive guidance markers and meticulous rigid programming. The Mobility for Manufacturing Applications thrust will address this potential impact.
- Robots that can be rapidly re-tasked through greater onboard task and situation knowledge will enable manufacturers to produce smaller lot sizes while taking advantage of the accuracy and quality of industrial robots. This impact will be pursued in the Autonomy for Manufacturing Applications thrust.

Standards Strategy

There are two main types of standards that industry needs for successful next generation robotics implementations in manufacturing: safety and performance standards. The projects in this Program collectively address the highest-priority needs in terms of safety for robot systems and vehicles and performance of perception, grasping, and planning and reasoning systems.

The major player in standards for manufacturing robotics and automation is the Robotic Industries Association (RIA). They develop the U.S. robot standards and represent the U.S. in the ISO standards committees. Industrial robotic vehicle standards are developed by the Industrial Truck Standards Development Foundation, which is responsible for the ANSI vehicle standards, while ASTM is active in standards for sensors and perception measurements. In response to new interest in standards for addressing knowledge representation and autonomy, the Program helped start relevant committees within the IEEE Robotics and Automation Society, led by NIST personnel.[21]

Robot safety standards are addressed through a leadership role played by EL staff in ISO/TC 184/SC 2 "Robots and robotic devices" and through the ANSI/RIA R15.06 robot safety standards committee. NIST's main role is in the area of human-robot interaction, a key requirement of manufacturers who want greater integration of people and robots in their assembly operations. A recent outcome is the adoption of ISO 10218, reducing the requirement of having robots separated by barriers. The robot safety standards are adopted by all industrial robot users and improvements provide immediate benefits to manufacturers in terms of greater flexibility and reduced cost[22]. Upcoming NIST-led enhancements will enable risk assessments of close human-robot collaborations, including determining allowable forces that a robot may safely exert on its human partner (ISO Technical Specification 15066, expected in early FY13), adoption of the new ANSI RIA version of the ISO standard (FY13). Longer-term, standards will measure how well humans are detected (FY15-16).

Industrial vehicle safety is addressed through the ANSI/ITSDF B56.x series of standards, which address the requirements for safe operation of automatic guided vehicles (AGV) and manned vehicles that have autonomous capabilities. EL staff members are improving the measurement techniques used by the systems to detect obstacles and people, expanding the scope of sensors that are allowed to be used on the vehicles, and improving methods enabling the vehicles to operate in close proximity to people. The standards are used by all manufacturers that have AGVs in their factories and also benefit the AGV and sensor manufacturers. In 2012, the ANSI B56.5 AGV

Safety Standard was adopted, permitting non-contacting safety sensors based on NIST measurement science contributions. Measurements that NIST is developing will characterize the visibility on shop floor vehicles (2015

Robot and sensor performance standards help manufacturers know which equipment best suits their needs, direct research efforts towards industrially-relevant solutions, and ensure a level playing field for vendors. There is a strong industry pull for performance standards for sensors that can identify parts and provide their locations and orientations. NIST leadership in ASTM has resulted in the first interoperability standard for 3D sensors (E2807), enabling plug-and-play for industrial sensors and in the development of a performance test method for Evaluating Static Pose Measurement Systems, which will be balloted later in FY12. The Program is developing the measurement science for additional ASTM sensor performance standards: for static object identification and range (FY14) and for volumetric sensor performance[23] (FY15). NIST has brought together the interested parties with the RIA to start to discuss a new version of their robot arm performance standards. Work has begun on measurement science for grasping and manipulation at the macro and micro size scales, less-mature technologies that have no current SDO activity. Outreach to SDOs to find appropriate hosts is underway.

Activity in knowledge representation and planning for greater autonomy has been in the academic community. Recently, manufacturers have shown interest because of their desire for greater flexibility and smaller batch sizes without painstaking robot reprogramming. Based on industry requirements gathered by NIST in a workshop at major trade show, we are developing semantic representations supporting a priori knowledge and static sensor updates, and metrics for evaluating the flexibility and agility of planners, to be submitted to the IEEE standards group in FY14.

How will knowledge transfer be achieved? Knowledge will be transferred through development of new or enhanced standards within the organizations listed above, through conferences and workshops, and through collaborating with industry partners.

MAJOR ACCOMPLISHMENTS

Outcomes:

Safe Human-Robot Interactions

- Harmonized ANSI/RIA R15.06 robot safety with the new ISO 10218 standards and with the Canadian standard (CAN/CSA-Z434-03 (R2008)) to avoid inconsistent safety requirements internationally, given that many manufacturers have factories in both the U.S. and Canada. A draft of the combined standard will be balloted in late FY2012.
- A revised draft of a technical specification (TS 15066 Robots and robotic devices — Collaborative robots) for the ISO 10218 standards, to provide guidance and procedures to users of the standards on how to incorporate collaborative tasks in their factories.
- A test device was developed for measuring the forces exerted by a robot on a person and tested on a prototype robot being developed by Rethink Robotics (Heartland Robotics). The device implements the requirements of the safety standard and is used to validate the biomechanical limits in the standard.

Sensing and Perception for Manufacturing Applications

- A first draft of a standard for static pose measurement systems (under ASTM E57) will be balloted before the end of FY2012.

Manipulation for Manufacturing Applications

- The ANSI/RIA R15.05 committee on robot performance standards was revitalized through meetings arranged by NIST, with the goal of developing new performance measures for modern robots that have more complex control systems and that need greater accuracy (as opposed to repeatability).
- A major product announcement in the medical diagnostic test area arose from CRADAS established to transfer technology in the micro- and nano-manipulation area.

Mobility for Manufacturing Applications

- The RIA and ITSDF communities were brought together to establish a working group to explore new standards for mobile-base robots.

Autonomy for Manufacturing Applications

- A new IEEE Robotics and Automation Society Standards Working Group on Knowledge Representation, with NIST leadership, was approved to address standard knowledge representation and planning methods for manufacturing.

Recent Impacts

Safe Human-Robot Interactions

- NIST personnel participated in drafting the ISO 10218 standards (parts 1 and 2), with special focus on the human-robot collaboration requirements. The standards were balloted in 2011 and have now been approved
  (ISO 10218-1:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Robots
  ISO 10218-2:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 2: Robot systems and integration.)

Sensing and Perception for Manufacturing Applications

- ASTM E2807 - 11 Standard Specification for 3D Imaging Data Exchange, Version 1.0, describes a data file exchange format for three-dimensional (3D) imaging data. This standard was created with NIST leadership. Although only published in 2011, the standard has been adopted by the main 3D imaging system vendors, including FARO, InteliSum, Inovx, Kubit, Leica Geosystems, Optech, Pointools, Quantapoint, Riegl, Trimble, and Zoller+Fröhlich. The standard will be used both in the U.S. and internationally.

Mobility for Manufacturing Applications

- ANSI/ITSDF B56.5-2012 defines the safety requirements relating to the design, operation, and maintenance of unmanned automatic guided industrial vehicles and automated functions of manned industrial vehicles. The latest version of this standard, adopted in 2012, includes many NIST-provided features, most notably performance measures to enable the use of non-contact bumpers on the vehicles. This allows increased speeds of vehicle and reduces the risks of injury. The standard is widely used in the U.S by automotive, pharmaceutical, general manufacturing, chemical, and food and beverage industries.[24]

Recognition of EL:

- 2010 Bronze medal award for developing open source software to support the simulation of robot work cells and mobile industrial vehicles. The software is also used for robot safety, to test applications in simulation before running them on real hardware.
- 2009 Government Open Source Conference Agency Award for Engaging Citizens, also awarded to the robot simulation software.
- 2010 Best paper award from Standards Engineering Society at the World Standards Day Paper Competition, for a paper surveying robot standards and evaluating how they can be used by different types of robots.

[1] PCAST, "Report to the President on Ensuring American Leadership in Advanced Manufacturing", June, 2011

[2] Green, T., "Robots, Re-shoring, and America's Manufacturing Renaissance," Robotics Trends, August 2, 2012.

[3] OMB-OSTP Science and Technology Priorities memo, June 6, 2012 http://www.whitehouse.gov/sites/default/files/omb/memoranda/2012/m-12-15.pdf

[4] "A Roadmap for US Robotics: From Internet to Robotics," CCC and CRA (NSF-funded), 2009, http://www.us-robotics.us/.

[5] Executive Office of the President, December 2009, "A Framework for Revitalizing American Manufacturing" http://www.whitehouse.gov/sites/default/files/microsites/20091216-maunfacturing-framework.pdf

[6] "Robotics in Manufacturing Technology Roadmap," Produced by Energetics, Inc., Sponsored by U.S. Department of Energy, October 2006.

[7] A Roadmap for US Robotics: From Internet to Robotics," CCC and CRA (NSF-funded), 2009, http://www.us-robotics.us/.

[8] Barajas, L., Thomaz, A., Christensen, H., "Ushering in the Next Generation of Factory Robotics & Automation," in "Challenges to Innovation in Advanced Manufacturing: Industry Drivers and R&D Needs," NISTIR 7723, November, 2009.

[9] It is estimated that 45% of the robot supply is taken up by 10% of the industry, primarily by companies that have more than 500 employees (mostly automotive), and that 90% of the potential users have not adopted robotics for manufacturing. (Data from World Robotics Statistics, International Federation of Robotics)

[10] ibid

[11] Bekey, G. et al., "Panel Report on International Assessment of Research and Development in Robotics," Produced by the World Technology Evaluation Center, Sponsored by the NSF, NASA, and NIMIB, Jan. 2006.

[12] Ibid.

[13] EUROP: European Robotics Technology Platform, http://www.robotics-platform.eu/cms/index.php?idcat=41&idart=391, April, 2011.

[14] "Robotics in Manufacturing Technology Roadmap," Produced by Energetics, Inc., Sponsored by U.S. Department of Energy, October 2006.

[15] In the NSF/CCC/CRA study, "Participants noted that research in robotics is rarely thoroughly evaluated and tested in well-defined, repeatable experiments"

[16] ISO 10218, ISO 13482, RIA/ANSI R15.06, ANSI/ITSDF B56.5.

[17] "The third industrial revolution, Special Publication by The Economist, April 21, 2012

[18] "Report to the President on Capturing Domestic Advantage in Advanced Manufacturing," produced by the Advanced Manufacturing Partnership Steering Committee Group, July 2012.

[19] Dynamic Measurement and Control for Autonomous Manufacturing Workshop Draft Report, Sponsored by NIST, October 2007, Columbia MD.

[20] Random bin picking is "the ability of vision-guided robots with appropriate tooling to pick haphazardly arrayed parts or components from a bin and place them for the next step in the manufacturing process." (definition from http://roboticsonline.worldpress.com/tag/bin-picking, February 2012)

[21] R. Madhavan, "RAS Standing Committee for Standards Activities—An Update on Recent Activities." IEEE Robotics and Automation Magazine, March 2011.

[22] According to the RIA, "Case studies suggest up to 30-40% reduction in floor space required and systems design cost savings of $100,000 per work cell" with the new ISO 10218.

[23] Volumetric sensing enables measurements of surfaces rather than points, which is essential for part inspection.

[24] http://en.wikipedia.org/wiki/Automated_guided_vehicle.