EL Program: Smart Manufacturing and Construction Control Systems

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

Summary: Optimization is a key performance objective to increase manufacturing productivity and improve product quality. To move beyond slow and costly trial-and-error methods requires making actual production measurements, analyzing the results according to models and simulations, determining actions that improve key performance indicators, and feeding these improvements back upstream for re-planning or re-design. This program provides the measurement science and standards that enable rapid reconfiguration, control, monitoring, and performance optimization of manufacturing activities within a smart factory. The work focuses on providing the technical basis for the definition and use of measurements, models and architectures, leading to standards that help manufacturers responsively produce best-in-class products with dramatically improved productivity, while maintaining high quality, safety, and security.

Objective: This program will develop and deploy advances in measurement science for sensing, modeling, and optimizing manufacturing activities in a smart factory, delivering results by 2016.

What is the problem? The Office of Science and Technology Policy (OSTP) and Office of Management and Budget (OMB) have called for focused support of R&D in "advanced manufacturing to strengthen U.S. leadership in the areas of robotics, cyber-physical systems, and flexible manufacturing" as a means to promote sustainable economic growth and job creation. [1] OSTP also identifies IT-enabled manufacturing, using modeling and simulation with real-time manufacturing data, as key to improving quality[2]. The Computing Community Consortium roadmap for U.S. robotics[3] identified adaptable and reconfigurable assembly as a critical capability for manufacturing. A broad consensus has emerged that smart manufacturing – the dramatically intensified application of *manufacturing intelligence* via advanced data analytics, modeling, and simulation – provides a comprehensive approach to addressing global competitiveness, skilled job retention and growth.[4] The importance of smart manufacturing is also reflected in the findings of the National Science and Technology Council (NSTC) Interagency Working Group on Manufacturing R&D, which identified Intelligent and Integrated Manufacturing as one of three opportunity areas for federal manufacturing R&D.[5] Although there is already a trend toward smart manufacturing and some progress is being made, "needed systemic infrastructural capabilities are yet to be delivered to mobilize a knowledge- and model-enabled process industry environment over the entire product and process lifecycle."[6]

Manufacturers still lack the ability to adapt automated production equipment and systems rapidly, reliably, safely, and cost-effectively to meet changing needs and requirements; and obtain, seamlessly integrate, and optimally use the full spectrum of real-time, actionable process information. Systems take too long to configure, and there is little ability to re-use existing automation components to extend capabilities[7]. The inability to get real-time production information at all points across a facility is the primary technical barrier impeding the deployment of smart manufacturing. The 2009 report from the National Workshop on Challenges to Innovation in Advanced Manufacturing emphasizes this, noting "an urgent need for standardized data formats and messaging capabilities among devices to harmonize systems; intelligent sensors; and improved data collection and control systems"[8]. To overcome these barriers, measurement science is lacking for **measurement and sensing** (what information can be sensed to measure the state of the smart factory), **modeling and simulation** (how well this

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[1] OMB-OSTP Science and Technology Priorities memo, July 21, 2010 http://www.whitehouse.gov/sites/default/files/microsites/ostp/fy12-budget-guidance-memo.pdf

[2] "Innovation and US-Based Manufacturing," HCSS/NITRD/CPS Group Meeting, Arlington VA- Dec 15, 2010.

[3] Computing Community Consortium, A Roadmap for US Robotics: From Internet to Robotics, May 21, 2009.

[4] Smart Manufacturing Leadership Coalition (SMLC) Public-Private Partnership Program Recommendations, Oct. 10, 2010.

[5] Manufacturing the Future: Federal Priorities for Manufacturing R&D, http://www.manufacturing.gov/pdf/NSTCIWGMFGRD_March2008_Report.pdf

[6] Smart Process Manufacturing: An Operations and Technology Roadmap, 2009 http://oit.ucla.edu/nsf-evo-2008/documents/SmartProcessManufaturingAnOperationsandTechnologyRoadmapFullReport.pdf

[7] IMTI, "A Report on Smart Assembly," December 1, 2006.

[8] Smart Process Manufacturing Engineering Virtual Organization Steering Committee, "Smart Process Manufacturing: An Operations And Technology Roadmap," November 2009.

information is used to model and simulate smart factory activities), and **optimization and control** (how best to use it to continually optimize manufacturing production).

Why is it hard to solve? Optimization itself is a hard problem; indeed, many optimization problems that are simple to formulate are known to require infeasible amounts of computing power for problems of useful scale. Optimizing the operations in a smart factory involving hundreds of individual unit processes is certainly not simple to formulate, either in defining the cost functions to minimize or determining the techniques to search for the minimum costs. Practical optimization takes the approach of abandoning the search for theoretical optimums and instead searches for sub-optimal solutions that are close. Such operations research optimizations are typically done with stochastic simulations that evaluate many options during the time available and picking the best one. Many techniques are well known and this is an active research area. There are many difficulties applying these techniques in the smart factory, however. In the area of **measurement and sensing**, it is hard to determine what the cost functions should measure, how the measurements should be made and used, and how to deploy the right sensors in the right places to make the measurements. **Modeling and simulation** are key technologies for optimization, but it is difficult to integrate real measurements into the models and simulations that use the measurements. Even when optimal plans can be determined, it is hard to use these plans to control the underlying smart manufacturing processes. Deployment of technology is also made more difficult by practical barriers: the conservative philosophy toward the risks of change of shop floor managers faced with intense competition, large capital investments in legacy systems, and the consequences of damaged equipment and worker injuries when deploying untested technology.

How is it solved today, and by whom? Manufacturers work around the problem by adopting proprietary “total solution” product suites that are internally connected but afford limited exchange to other systems. Optimizations that are done within these systems are hard-coded and rely on brittle data collection connections to proprietary equipment. The European Commission’s Seventh Framework Programme (FP7) is funding research on integration of industrial technologies to improve European competitiveness through a transformation from resource-intensive to knowledge-intensive industries. Key information modeling research is taking place at universities such as the Royal Institute of Technology in Sweden and the University of Bath in the UK, affecting international standards. Although these results can benefit U.S. companies, the risks of letting other countries lead is the disproportionate benefit in either standards content or speed to market gained by foreign companies. Industry groups such as Manufacturing Enterprise Solutions Association (MESA) International are working the problem through best practices and guidance, and the online Key Performance Indicator (KPI) Library portal makes thousands of practical KPIs available to its members. However, the cottage industry of hundreds of “manufacturing optimization” consultants testifies to the state of industry practice as an art rather than a science.

Why NIST? The program addresses EL’s mission to promote U.S. innovation and industrial competitiveness by anticipating and meeting measurement science and standards needs for technology-intensive manufacturing, through the program’s technical contributions that underpin standards for optimizing smart manufacturing systems on the shop floor. Applying core competencies in intelligent sensing, modeling and optimization, with staff expertise in electrical engineering, mechanical engineering and computer science, the program will develop the measurement science that informs standards for optimization-related information and performance. The work complements research done by industry and academia through the program's focus on measurement needs that cut broadly across the discrete part production, continuous process and batch manufacturing sectors. NIST's recognized objective neutrality and longer-term dedication to the standards process are also essential to our role in this program.

What is the new technical idea? The new technical idea is to combine concepts from control theory and operations research to "automate the optimization" in a smart factory, for which the program develops the measurement science needed to achieve this automation. Recognizing that "if you can't measure it, you can't control it," and the related adage, "if you can't model it, you can't control it," the program has three thrusts: **measurement and sensing**, **modeling and simulation**; and **optimization and control**. Each thrust encompasses activities that bridge unit processes (such as machining or inspection) to high-level factory scheduling (such as done by manufacturing execution systems). Optimization that is internal to equipment, such as generating optimal speed profiles of motors, is out of the scope of this program. Similarly out of scope is the optimization of product design, such as finite-element analysis of connector stiffness. Following the control viewpoint, the program targets the inputs needed for optimization, and determines what should be measured (the *measurands*) and how they should be measured (the *measurements*). Central to the technical idea of automating the optimization is the development of methodologies and architectures for achieving this. By combining smart measurement, modeling and simulation into an automated optimization architecture, the program hopes to make it possible for manufacturers ranging from small shops to major industrial companies to rapidly configure and operate their factories as effectively and efficiently as possible.

Why can we succeed now? There is heightened awareness of the productivity increase that can be achieved by optimizing on the shop floor. Manufacturers are aggressively seeking ways to improve use of their manufacturing resources so they can better innovate and competitively bid for global jobs. This is creating new opportunities and imperatives for sensor and data fusion to enhance measurement and optimization of production processes, increasing efficiency, quality, and manufacturers' flexibility to meet changing customer demands. Recent standards arrivals, such as MTConnect and the Quality Information Framework, have attracted substantial industry participation in these areas. At the national level, the Smart Manufacturing Leadership Coalition (SMLC) has defined priority actions for developing robust data collection frameworks and establishing consistent data protocols, interfaces and communication standards. EL staff with strong engineering and software experience in the manufacturing domain, combined with testbed experience and a long-term shop-floor presence, position NIST to bring necessary resources and make immediate progress.

What is the research plan? The program will establish a virtual factory testbed in which NIST researchers will collaborate with industry and academic partners to develop, test, and standardize measurement science that supports optimizing manufacturing and assembly tasks in the factory. Technical outputs that advance the state of the art in performance measures, modeling, simulation, and optimization will be published in archival journals. Standards outcomes that guide practitioners who implement these aspects of optimization will be taken through standards development organizations. Program work will take place in projects divided among the three thrusts. In the **measurement and sensing** thrust, three projects target secure, reliable, and standardized data collection. The Factory Cybersecurity project will deliver by 2014 the technical basis for a set of functional standards for securing smart manufacturing communications and control infrastructure against cyberattack. Project staff will work closely with ITL, ISA, and the Smart Grid Office for delivery to the wide customer base. The Performance Measurement of Equipment Networks in Smart and Wireless Factories project will deliver by 2014 a unified testing framework that measures the performance of smart sensors, protocols and architectures that include both traditional wired systems and wireless devices. The Key Performance Indicator Effectiveness project will define new and better definitions for key performance indicators and key characteristics essential to enabling optimized manufacturing processes and improved product quality. In the **modeling and simulation** thrust, two projects focus on providing the information models and simulation architectures needed to support optimization decision-making. The Manufacturing Modeling and Simulation project defines and uses models of manufacturing systems and simulations of system components to enable manufacturing performance measurement and optimization research. The Measurement Science for Integration of Robotics and Automation Control Systems project will develop test methods to validate draft standards for robot control architectures and protocols, serving as the primary driver for the smart manufacturing testbed to demonstrate the effectiveness of information models, protocols, and architectures for optimizing performance, delivering results through standards bodies by 2014. In the **optimization and control** thrust, the Measurement Science for Optimal Production Planning project will develop, test, and standardize information covering the outputs of optimization: factory plans, schedules, and optimal programs, linking especially through the robot control integration exemplar.

How will teamwork be ensured? The program involves staff mainly from the Networked Control Systems Group of the Intelligent Systems Division, ensuring intra-program teamwork on a daily basis. The program is closely related to the Systems Integration for Manufacturing and Construction (SIMCA) program, and teamwork with that program has been coordinated through a shared manufacturing architecture, unified standards landscape, and direct use of SIMCA outputs covering product manufacturing information. Teaming with the other smart manufacturing programs will be coordinated likewise using the architecture and standards landscape, with the smart manufacturing testbed serving as a shared physical resource. Program members also participate in industry groups, such as the MTConnect Institute, the National Modeling and Simulation Coalition, the Open Modular Architecture Controller Users Group, and the Smart Manufacturing Leadership Coalition.

What is the impact if successful? Potential impacts include the reduction in time to integrate equipment and set up new processes, improved quality and equipment productivity through optimization using real-time information collection and analysis, and increased productivity of engineering staff who can focus on value-added production techniques rather than ad hoc equipment connection. Impact measurement will be done via the Open Modular Architecture Controller (OMAC) Users Group, part of the Automation Research Corporation (ARC), which continually refines business case metrics to justify member participation. These metrics originate with the participating companies, and we will also work with the EL Applied Economics Office to determine shop-floor productivity metrics. Our information modeling and testing work has enjoyed wide participation from end user stakeholders such as Ford, General Motors and

Chrysler, Caterpillar, John Deere and Boeing, and defense industry manufacturers such as Honeywell and Lockheed-Martin. These companies provide in-kind support of engineering staff in activities ranging from requirements gathering to standards development and pilot testing.

What is the standards strategy? The development and adoption of standards for equipment and applications in smart factories is critical to achieving widespread deployment of optimization and associated productivity gains. The overall program standards strategy is to identify standards gaps and develop measurement science where there is substantial industry backing, and partner with industry to validate draft standards already underway. For the measurement and sensing thrust, the ISA and the IEEE are the key standards development organizations for the work related to industrial control cybersecurity and wireless networking. Functional standards for cybersecurity are being developed through the ISA's Security Compliance Institute (ISCI); performance test metrics are being pursued through IEEE's Conformity Assessment Program. Standards for information representing real-time production information are being developed through the Association for Manufacturing Technology, the Dimensional Metrology Standards Consortium, and the Society of Automotive Engineers. Standards development through ISO TC 184 ties this program together with the SIMCA program; SC 4 covers product manufacturing information, and SC 5 covers factory architecture and performance measures. The top five standards needs are,

for **measurement and sensing**:

1. Wireless sensor networks performance measurement standards (through IEEE, ISA, IETF) to improve the capabilities of wireless networks in demanding factory environments;
2. Compliance tests for new parts of ISA-99 series of standards for industrial control cybersecurity to provide increased confidence in security of sensor networks (ISA);
3. Standard definitions and effectiveness metrics for KPIs to enable automated optimization (ISO, MESA).

For **modeling and simulation**:

4. MTConnect standard for resource information to enable real-time optimization and traceability of individual products to reduce life cycle costs (AMT).

For **optimization and control**:

5. Quality standards for plans, rules, resources, and results to enable better integration of quality assurance and control across manufacturing activities (DMSC, AMT, PDES).

How will knowledge transfer be achieved? Knowledge will be transferred implicitly via our participation in standards validation pilot projects with selected industry partners, and explicitly via reference implementations and testing software made available through open-source mechanisms such as SourceForge. We will participate formally with the STEP Manufacturing Team TC 184 SC4 WG3 T24 and the PDES Inc. CAx-IF implementers forum. Publications are a key part of our knowledge transfer, and the program's results will be submitted to archival journals for which we have had past success, such as the International Journal of Production Research, the International Journal of Computer Integrated Manufacturing and the International Journal of Standardization. The program will continue the appointments of four guest researchers, and solicit short-term sabbatical appointments from visiting professors that have proven effective. All software produced will undergo testing as required by the EL software quality management policy.

Major Accomplishments:

- **Impact:** EtherNet/IP, Ethernet Industrial Protocol, published by the Open DeviceNet Vendors Association (ODVA) and by their account "the most developed, proven and complete industrial Ethernet network solution available for factory automation." ODVA's performance testing program uses the NIST-developed EtherNet/IP Test Tool.
- **Impact:** ANSI/ISA-99.01.01 and ANSI/ISA-99.02.01, Industrial Automation and Control Systems Security, published internationally as IEC 62443-1-1 and IEC 62443-2-1, and associated NIST SP 800-82 for Industrial Control Cybersecurity, downloaded over one million times since publication in 2007.
- **Impact:** I++ DME 1.7, Inspection for Dimensional Measurement Equipment, implemented by the majority of coordinate measurement machine (CMM) software and equipment vendors worldwide, and used by many U.S. manufacturers such as Caterpillar, John Deere, Lockheed Martin, Pratt & Whitney and General Electric.
- **Impact:** DMIS 5.2, Dimensional Measuring Interface Standard, published as ISO 22093 and ANSI 105.2-2009 Part 1. All CMM software vendors worldwide execute DMIS programs, and several major vendors generate DMIS programs. Unigraphics has been certified by the DMSC using the NIST DMIS conformance test software. Many U.S. manufacturers reduce part inspection time and cost by using DMIS, such as Chrysler, John Deere, General Electric, Honeywell and Lockheed Martin.
- **Outcome:** IEEE 1451.0, 5, 7, Standard for a Smart Transducer Interface for Sensors and Actuators, published internationally as ISO/IEC/IEEE 21450, 21451-5, 21451-7, respectively.
- **Outcome:** MTConnect Version 1.2. This standard, published by the Association for Manufacturing Technology, defines a protocol and information model for acquiring real-time information from production equipment. NIST conducted validation testing and performance measurement for the standard.
- **Outcome:** ISO 10303 Application Protocol 238. This standard was published in 2007 following extensive validation testing by NIST in pilot projects.

Recognition of EL:

- Kang Lee, 2010 Edward Bennett Rosa Award, for outstanding leadership and technical excellence in the initiation, development and worldwide adoption of the IEEE 1588 Precision Time Protocol.
- Jim Gilsinn, Best Paper Award, ISA Process Measurement and Control Division, "Test Tool for Industrial Ethernet Network Performance," 2009.
- Jim Gilsinn, InTech Magazine Cover Story, "Testing, comparing industrial Ethernets," August 2009.
- Bill Rippey, Metromeet Best Paper Award, "Certification Testing of DMIS Implementers," March 2009.
- Jim Gilsinn, October 2006, ISA Standards & Practices Award for work on publishing ISA-99.02.01
- John Horst and Keith Stouffer, NIST Bronze Medal 2006, for leadership in dimensional metrology data exchange standards.
- John Horst, AIAG Outstanding Achievement Award 2005.

- Fred Proctor and Keith Stouffer, Department of Commerce Gold Medal 2005 (leadership in industrial control system security standards).
- Bill Rippey, Standards Engineering Society World Standards Day Best Paper Competition, Second Place, "We need better information Connections for Welding Manufacturing," 2004.