EL Program: Smart Manufacturing Systems Design and Analysis

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

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Summary:

Smart Manufacturing has the potential to fundamentally change how products are designed, manufactured, supplied, used, remanufactured and eventually retired. Current smart manufacturing implementations are mostly at the plant level, and use information technology, sensor networks, computerized controls, and production management software to improve efficiency[1]. The focus of the program is design and analysis of smart manufacturing system (SMS) that will enable industries to implement at the enterprise level, implementing real-time control and data analytics throughout the extended enterprise. Implementing predictive data analytics across the supply network offers new opportunities for process optimization and emphasize prediction in the PDSA (plan, do, study, act) cycle.

While industry is making progress in developing and implementing smart manufacturing technologies, the systemic cyber-physical[2] infrastructure and measurement science, standards, and protocols needed to deliver and deploy a large scale smart manufacturing environment remains to be developed. The cost of developing and implementing open software platforms and technologies based on common standards remain high, creating a significant barrier to entry particularly for small- and medium-size enterprises (SMEs). The Smart Manufacturing Systems Design and Analysis program will address these issues and explore potential opportunities for dramatically rethinking the manufacturing system life cycle with a focus on assembly-centric production[3]. For a smart manufacturing system, the program will build the following: 1) reference architecture and open solution stack to enable and assess the composable SMS, 2) modeling methodology and associated tools to predict, assess, and optimize the operational performance, 3) data analytics and associated methods and tools to enable adaptive system, and 4) methods and tools for system performance assurance. The results of this program will apply to broad industry sectors, and will lead to internationally accepted measures and practices.

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[1] Efficiency is the top key performance objective needed to achieve the future vision for manufacturing, with a focus on agility, asset utilization, and sustainability.
[2] Cyber-Physical System (CPS) is a system of collaborating computational elements controlling physical entities.
[3] Batch and continuous manufacturing systems will be considered as part of plans for future program expansion.

DESCRIPTION

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

Objective:
Deliver measurement science, standards and protocols, and tools needed to design and analyze SMS based on a cyber-physical infrastructure for digital and manufacturing systems by 2018.

What is the problem?
Smart Manufacturing System (SMS) has the potential to fundamentally change how products are designed, manufactured, supplied, used, remanufactured and eventually retired. In the context of manufacturing, "smart" systems are adaptive systems[4] with differing levels of autonomy. Built upon advanced cyber physical systems and data analytics, smart manufacturing system will enable rapid realization of products, dynamic response to changing demand, and real-time performance optimization of production and supply chain networks. Data analytics plays a critical role in enabling smart manufacturing. The recent Office of Science and Technology Policy (OSTP) memo[5] identified big data analytics as one of the key multi-agency priorities. A recent industry report[6] emphasized the application of big data analytics to manage complex manufacturing processes and supply chains. The President made revitalizing manufacturing a top U.S. priority, and launched the Advanced Manufacturing Partnership (AMP). The AMP Steering Committee made high-level recommendations[7] that will set the stage for advanced manufacturing to thrive in the United States. Industry, academia, and government entities have formed the Smart Manufacturing Leadership Coalition (SMLC) to develop the smart manufacturing platform. The SMLC report[8] outlines the outcomes and goals for SMS and identifies ten priority actions, which include creating modeling and simulation platforms, data collection and management systems, and enterprise wide integration systems for smart manufacturing.

While industry is making progress in developing and implementing smart manufacturing technologies, the systemic cyber-physical infrastructure and measurement science, standards and protocols needed to deliver and deploy a large scale smart manufacturing environment remains to be developed. The next generation of smart manufacturing system needs to be developed by composing advanced manufacturing and IT services, yet the composition is not possible due to a lack of a smart manufacturing reference architecture and solution stack. There is a big measurement science gap between the existing models of manufacturing systems and the analytical models that are required to precisely characterize manufacturing systems for performance assurance. Also, the cost of developing and implementing open software platforms and technologies based on common standards remain high creating a significant barrier to entry, particularly for small- and medium-size enterprises (SMEs). The program will address these issues and explore potential opportunities for dramatically rethinking the manufacturing process

4 Adaptive systems are considered to be self-aware and predictive systems with the ability to make decisions for diagnosis, prognosis, and optimal system performance with incomplete and often uncertain information.
5 M-12-1, Memorandum for the heads of executive departments and agencies, http://www.whitehouse.gov/sites/default/files/m-12-15.pdf
6 Manufacturing the future: The next era of global growth and innovation, MGI Global Institute, http://www.mckinsey.com/insights/business_technology/big_data_the_next_frontier_for_innovation
7 http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf
8 https://smartmanufacturingcoalition.org/sites/default/files/implementing_21st_century_smart_manufacturing_report_2011_0.pdf

with a focus on assembly-centric production[9]. The program will build the following for a smart manufacturing system: 1) reference architecture and open solution stack to enable and assess the design and operation, 2) modeling methodology and associated tools to predict, assess, and optimize the operational performance, 3) data analytics and associated methods and tools to enable adaptive system, and 4) system performance assurance methods and tools to minimize risk. The results of this program will apply to broad industry sectors, and will lead to internationally accepted measures and practices.

Why is it hard to solve?

Smart Manufacturing System (SMS) comprise a network of highly complex, advanced technologies. Integrating these technologies is difficult and costly. The resulting network creates an environment that complicates efforts to control these SMS significantly. However, recent technology advances in machine learning and mathematical and information modeling can be applied in novel ways to enable and assess SMS. The composition of advanced manufacturing components and IT services using newly defined reference architecture and solution stack forms the basis for open SMS definition. The challenge for the reference architecture is to develop functional decomposition models of large, evolving, and heterogeneous domains of factories and production networks. The data analytics challenge is both in the organization and extrapolation data and in the definition of analytical methods. The heterogeneous and proprietary solutions for data capturing, preprocessing, fusion, streaming, dimension reduction, and filtering need a standard-based approach to address challenges of traceability, uncertainty quantification, security, and data provenance. In the information and analytics modeling, the scalability, composability[10], compositionality[11], and interoperability[12] of models and algorithms are needed to construct predictive capabilities from machine level to enterprise level and supply network level for system performance assurance. Two fundamental measurement science challenges for performance assurance are 1) measure, monitor, and control the performance measures, and 2) trace performance problems to the source. Understanding both correlations and causation needs new statistical models with uncertainty quantification. The real challenge is to reduce information overload for manufacturing by order of magnitude and filter useful information to get same level of insights with less data. We need to develop mathematical and computational models of these filters in such a way that they do not discard useful information and mature from big data to better and minimal data.

How is it solved today, and by whom?

While there is progress in developing and implementing smart manufacturing technologies, the systemic cyber-physical infrastructure and measurement science, standards, and protocols needed to deliver and deploy a large scale smart manufacturing environment remains to be developed. The global efforts outlined below are a good start towards solving the problem, but the issues are currently solved using proprietary technologies that are difficult to integrate across the industry, and are expensive for SMEs.

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[9] Batch and continuous manufacturing systems will be considered as part of plans for future program expansion.

[10] Model composability is concerned with techniques (modeling formalisms) for developing a whole model of a system from the models of its sub-systems. System composability is more challenging – modularity, state independence etc. come into play.

[11] The property of the system that the whole can be understood by defining the parts and how they are combined.

[12] Interoperability deals with implementation issues, and integratability with network. The IEEE glossary defines interoperability as the ability of two or more systems or components to exchange information and to use the information that has been exchanged.

In the United States, SMLC aims to develop the Smart Manufacturing (SM) platform, but its main focus is on processes. The Industrial Internet is a term coined by GE[13] and refers to the convergence of intelligent devices, intelligent networks, and intelligent decisions. Ford Michigan Assembly plant serves as a model of modern, efficient and flexible manufacturing, designed so that 80% of the robots in its body shop could be reprogrammed to build several different vehicles, the flexibility possible with integrated automation and information.

In Europe, the goal of the German government's Industry 4.0[14] project is to develop the intelligent factory (Smart Factory), characterized by adaptability, resource efficiency, and ergonomics. Technological basis are cyber-physical systems and the Internet of Things (IoT). According to International Data Corporation (IDC), the IoT and the technology ecosystem are expected to be an $8.9 trillion market in 2020[15]. IoT European Research released the Cluster Book[16] providing inputs to the Horizon 2020 Programme. In Japan, the Ministry of Economy, Trade and Industry (METI) announced a strategy for "Smart Convergence"[17] to develop technology independent and "Leading Edge Integrated Industries" through digitization and networking.

Why NIST?

This program is aligned with the EL mission to promote U.S. innovation and industrial competitiveness in areas of critical national priority. The program researchers have extensive measurement science expertise in life cycle assessment, product and process information modeling, and system interoperability, best practice guidelines, and standards-related research. All are necessary to implement the technical idea and research plan described below.

The President's Council of Advisors on Science and Technology (PCAST) in its 2011 report[18] stated that the Federal Government can promote advanced manufacturing in the U.S. by focusing on three broad areas of opportunity: advancing new technologies, supporting shared infrastructure, and dramatically rethinking the manufacturing process. This program addresses the key opportunity identified by the PCAST for dramatically rethinking the manufacturing process, with advanced technologies and shared infrastructure in the form of standards and tools, including software, guidance, and reference data. NIST can play a role in bridging the gap between industry requirements and fundamental measurement science through delivery of practical artifacts (standards, best practices, and benchmarking) derived from strong industry collaboration.

What is the new technical idea?

The objective of this program is to deliver measurement science, standards and protocols, and tools needed to design and analysis (predict, assess, optimize, and control the performance) of smart manufacturing system. The new technical idea to achieve this objective is the following: 1) Define what the performance of SMS is and how we measure it in a computational and mathematical sense, 2) Define methods to develop analytical and compositional models of SMS, 3) Define methods to collect, analyze, and utilize data required to predict, assess, optimize, and

[13] http://files.gereports.com/wp-content/uploads/2012/11/ge-industrial-internet-vision-paper.pdf
[14] http://www.plattform-i40.de/
[15] http://www.idc.com/getdoc.jsp?containerId=243661
[16] http://www.internet-of-things-research.eu/pdf/IERC_Cluster_Book_2012_WEB.pdf
[17] http://www.meti.go.jp/english/press/2011/0811_01.html
[18] http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf

control the performance of SMS, and 4) Define a reference architecture and methodology to implement methods and tools to predict, assess, optimize, and control the performance of SMS from a system engineering perspective.

The major projects of the **Smart Manufacturing Systems Design and Analysis** program are listed below.

1. Build reference architecture and open solution stack to enable and assess composable smart manufacturing systems. The new technical idea is to develop an effective systems engineering methodology for developing, maintaining, and using the reference architecture[19] and solution stack[20]. Smart Manufacturing Reference Architecture will be an authoritative source of information that guides and constrains the instantiations of multiple architectures and solutions.
2. Build modeling methodology and associated tools to predict, assess, and optimize the operational performance of smart manufacturing systems, including uncertainty propagation and compositional modeling. The new technical idea is to bring together the conceptual modeling, information modeling, and behavior modeling paradigms to enable analytical frameworks that use domain-specific and mathematical modeling tailored to application in smart manufacturing.
3. Build data analytics and associated methods and tools to enable and assess diagnostics and prognostics for smart manufacturing systems in real time. The new technical idea is to develop open protocols, analytical models, implementation frameworks and standards to enable the application of data analytics to turn data into insights and actions. Towards this end, this project will deliver an analytical framework for real-time[21] improvement of dynamic production system efficiency.
4. Build system performance assurance methods and tools for smart manufacturing systems (including, e.g., automated testing). The new technical idea is to develop measures of performance, such as metrics for energy and material for sustainability, in addition to more traditional measures including cost, quality, reliability, and productivity as the basis for measuring the performance of individual processes and system.

The results of these projects will enable the convergence of intelligent devices, intelligent networks and intelligent decisions. The results will further enable information integration to support agile supply networks, real-time monitoring and controlling of manufacturing plants and assets, and rapid customization and realization of products.

Why can we succeed now?

The convergence of intelligent devices, intelligent networks and intelligent decisions is enabling information integration to support agile supply networks, real-time monitoring and controlling of manufacturing plants and assets, and rapid customization and realization of products. This is also emphasized by the "Future of Manufacturing" project report[22] *"... smart processes further enabled by advanced software and digital technologies will continue to alter the productivity and quality of production processes for many decades to come."*

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[19] Reference Architectures capture the essence of existing architectures, and the vision of future needs and evolution to provide guidance to assist in developing new system architectures. The Reference Architecture provides a common vocabulary and taxonomy, a common (architectural) vision, and modularization and the complementary context.

[20] A set of different programs or application software that are bundled together in order to produce a desired result or solution.

[21] A real-time system is hard to define precisely: it may loosely be defined as any system where the need to meet task deadlines significantly affects the design, operation, and evaluation of the system.

[22] http://www.deloitte.com/assets/Dcom-Global/Local%20Content/Articles/Manufacturing/dttl_WEF_The-Future-Manufacturing_4_20_12.pdf

Apart from the research initiatives to boost U.S. manufacturing, the critical technologies required for Smart Manufacturing have evolved and matured. For example, sensor networks, automated controls, planning and predictive models, plant performance optimization software, cyber-physical systems, security, and other related technologies are currently available in the market. This, coupled with advances in model based engineering, systems integration technologies, open data analytics platforms, multi-scale physical system modeling, engineering information systems, and decision support methodologies, provides the critical foundation for success and aid performance assessment and decision making at all levels.

The key to a successful program is a strong collaboration with industry sectors, especially SMEs. Outcomes of this program are anticipated to reflect the complexity and dynamics of real manufacturing systems. The outcomes regarding architecture and analytics modeling will be derived from data-driven approach using input data sets and its relevant metrics sets for performance assurance. The overall outcomes will include standards and open solutions that will help U.S. manufacturing sector and especially SMEs to address the complexity and dynamics of real manufacturing systems. This program will build a broad interface with manufacturing companies for capturing requirements and designing, testing and validating the models. Also, EL staff has the necessary mission, expertise, and relationships with key industry stakeholders and standards development organizations necessary to further the advances and trends. To succeed now, this program will also explore research collaboration with the Institutes for Manufacturing Innovation (IMIs) proposed under National Network for Manufacturing Innovation (NNMI)[23].

What is the research plan?

The research plan is organized into architecture and modeling thrust and predictive analytics and performance assurance thrust. The detailed plan is described in the individual project plans.

The architecture and modeling thrust has two major projects:

1. **Reference Architecture for Smart Manufacturing Systems:** The research plan is geared to achieve necessary contributions to develop successful reference architecture and solution stack. The architecture framework will be developed to provide conceptual guidelines for developing system architectures, tools, and methodologies for designing the architectures, general principles, knowledge base and models of the smart manufacturing system, and experimental methods for architecture assessment on increasingly complex collections of smart manufacturing systems descriptions. In FY14, the research emphasis will be to build architecture framework for SMS.
2. **Modeling Methodology for Smart Manufacturing Systems:** We have two threads of existing work to draw upon. Based on the previous work on the Sustainable Process Analytics Formalism in the Sustainable Manufacturing program and Decision Guidance Modeling Language (DGML), we will develop a general architecture for analytical frameworks. We will develop formal methods and tools for dynamic composition of manufacturing components (e.g., resources, equipment, hardware, and software) models to facilitate smart manufacturing system prediction and performance assurance. The formal models of components of SMS will be described at different levels of abstraction, namely, informational, mathematical, and behavioral. In order to predict and assure system level

[23] http://manufacturing.gov/nnmi.html

performance for different manufacturing scenarios, we need these models to be dynamically composable in an analytic environment, representing the larger production system. Based on international standards, we will develop methods of verification and validation and requirements traceability for SMS. The first task is to define requirements for analytical frameworks for SMS. In FY14 we will develop an architectural description of analytical frameworks, based on the requirements analysis and the previous work in the sustainable manufacturing program. Also in FY14 we will complete the refinement of the DGML.

The predictive analytics and performance assurance thrust has two major projects:

3. **Real-Time Data Analytics for Smart Manufacturing Systems:** To understand the predictive analytics workflow, this project in FY14 will focus on the following research areas: 1) Requirements analysis and the state of the art in manufacturing data management (volume, velocity, variety, veracity), 2) Analysis of predictive modeling techniques, rules for analytical model composition, metrics, and optimization methods and tools, 3) Identification of standards to represent a myriad of predictive modeling techniques, such as PMML[24], to fully support data analytics for manufacturing applications, and 4) Requirements analysis of interactive data visualization for analytics. Data visualization is an art and a science unto itself, and there are many techniques that can be used to get insights from the data.
4. **Performance Assurance for Smart Manufacturing Systems:** In FY 14, the project will attack the problem of performance assurance from multiple directions: 1) Identify the unique characteristics for performance issues and metrics for SMS, 2) Develop methods for interpreting metrics in terms of the performance objectives for SMS, 3) Identify approaches to address performance deviation, and 4) Demonstrate the use of performance measures in a system context. The metrics for performance assurance will be approached separately for each of the three performance objectives, namely sustainability, agility, and asset utilization. Results from this project will contribute to standards development activities within ASTM E60.13.

How will teamwork be ensured?

The program staff is drawn from Systems Integration Division (SID), Intelligent Systems Division (ISD), and Applied Economics Office (AEO) from EL and Information Technology Lab (ITL). The individual project plans provide details of the coordination of research activities and external collaborations through CRADAS, cooperative research agreements, contracts, and SBIRs. The program will have monthly status updates, monthly program meetings, quarterly reviews, and research seminars. This program will closely work with (1) Smart Manufacturing Operations and Control program for work related to methods to evaluate real-time system diagnostics and prognostics of an actual factory, cyber security, systems interoperability and performance of networked machine tools and robots (2) Measurement Science for Additive Manufacturing program for work related to methods and protocols to enable, assess, and assure rapid design-to-product transformation through end-to-end digital implementation of additive manufacturing, and (3) Robotic Systems for Smart Manufacturing program for work related to methods and protocols to assess and assure robot systems performance for smart manufacturing. The overall objective of the program will be delivered through the outputs, outcomes and impacts from the projects.

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[24] The Predictive Model Markup Language, an XML-based markup language developed by the Data Mining Group. It allows users to develop models within one vendor's application and use other vendors' applications to visualize, analyze, evaluate or otherwise use the models.