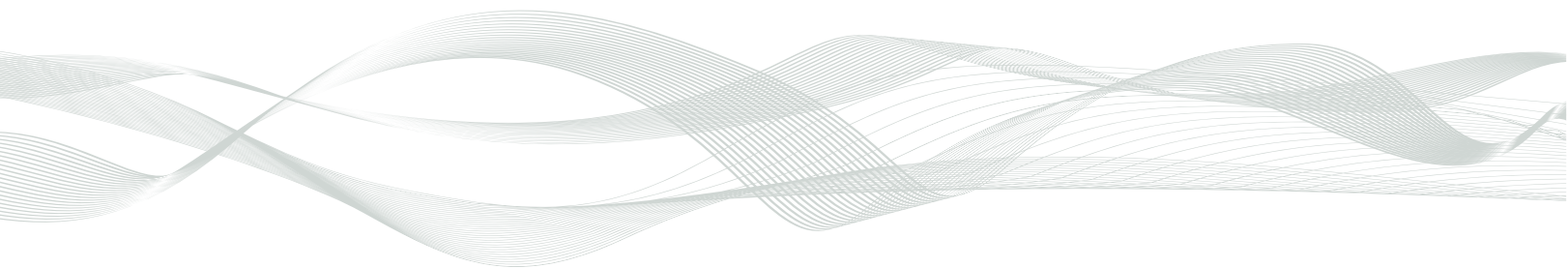


# **National Workshop on** **Challenges to Innovation in** **Advanced Manufacturing**

## **Industry Drivers and R&D Needs**

November 3-4, 2009





# Challenges to Innovation in Advanced Manufacturing: Industry Drivers and R&D Needs

November 3rd and 4th

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# Distributed Power-aware Machinery as a Foundation for Next Generation Sustainable Manufacturing

Dr. Fred M. Discenzo, Dr. Ram Pai, Dan Carnahan, P.E.  
Rockwell Automation

## I. Introduction

The U.S. manufacturing landscape is changing dramatically. Future markets will favor manufacturers that demonstrate responsible behavior with regard to energy usage, waste disposal and recycling. To compete, future manufacturers must maximize economic value-add from intellectual and physical capital investments, operate as part of a larger ecosystem of linked environmentally responsible global customers, suppliers, and partners. True leaders of tomorrow will play a global leadership in innovation of novel products and solutions. The transition to sustainable manufacturing must be done in the context of increasingly complex manufacturing processes and connected processes and enterprises. Organizations that are cognizant of these trends and accordingly shape their strategies and execute their tactics will define the winners in the next decade.

## II. Critical Drivers

The events surrounding 9/11 coupled with recent worldwide financial instability, aging workforce, volatility and insecurity of world energy supplies, and the need for environmental stewardship foreshadow an onslaught of a dramatic shift in values and priorities that is beginning to transform how consumers behave and manufacturers operate. Changes in technology, public policy, world security, and the financial and energy markets changes are among the factors accelerating the change in manufacturing. We see five major drivers that are transforming virtually every manufacturing sector in the US. These drivers are:

No	Drivers	Expectations
1	Energy & Waste	Effective utilization of resources to reduce waste and energy consumption, while optimizing production.
2	Safety & Security	Inherent Security and Safety of human, physical and intellectual capital across the connected supply chain.
3	Social Responsibility	Assessment and availability of information on Carbon and GHG emissions across the Product Life Cycle.
4	Harmonized Standards	Supply chain integration with availability and automated interpretation of digitized global standards across interoperable systems.
5	Globally Linked Enterprise	Global communication supporting a fabric of enterprises capable of exchanging and making decisions on information in real-time across the globe.

## II. R&D Needs

Specific developments are needed to efficiently promote the transition to a new manufacturing paradigm. There are seven areas of R&D need that will provide the foundation for manufacturing success in 2025. These areas are:

No	R&D Needs	Scope of Development Required
1	Sensing and measurement	Cost effective distributed sensing for energy, waste, process fluids, and airborne chemicals. Sensor fusion & wireless-self-powered sensors coupled with smart sensor networks.
2	Modeling & Simulation	Design and operational (i.e. control) models for sustainability
3	Dynamic link to plant manufacturing equipment and energy sources	Standards to support dynamic grid interface and linkages to plant MES and level 0/1 plant control to drive sustainable manufacturing and optimal economic performance.
4	Knowledge	Standardized approach needed for encoding process and product information –critical gap now beginning to occur.
5	Distributed energy & energy storage	Reference implementations based on Smart Grid standards to accelerate the adoption of energy aware eq. & processes.
6	Manufacturing Technology	New Pinch and other manufacturing with less energy, smart energy-aware machines and controllers, more efficient OEM equipment.
7	Methodologies for agile integrated manufacturing	Vertical and horizontal integration capabilities to support demanding requirements for capturing core capabilities and integration of those capabilities up and across the supply chain Mechatronics standardization and integration.

The topic area noted as “*Methodologies for agile integrated manufacturing*” is considered foundational and will form the cornerstone for future sustainable manufacturing. It is essential to provide a standard framework for distributed plant machinery such as ovens, fryers, boilers, fans, pumps, and other process equipment to exchange information on energy and process information in real-time and to respond to dynamic information provided by the grid in a timely and coordinated manner. This permits unprecedented capabilities for dynamically altering plant operations in an effective way to protect production processes and safeguard machinery and personnel while achieving targeted energy usage and manufacturing sustainability objectives. A representative framework for smart distributed energy-aware machines is provided by distributed agents. This framework, based on a biological analogy, has a rigorous underpinning and has shown to provide superior performance in a variety of complex and critical manufacturing processes<sup>1</sup>. There is a need to explicitly embed standard energy, risk, and economic protocols to permit this open, integrated system to dynamically link process equipment with plant scheduling and machinery control. As shown in the plant diagram multiple distributed processes must be coordinated and scheduled in real time to achieve new performance levels in energy utilization, waste reduction, and sustainable production. The scope must include plant facility services, supply chain partners, energy providers and customers.



## V. Summary

Recent events have triggered an irreversible change in manufacturing and necessitated the rapid transition to environmentally sustainable and socially responsible manufacturing. The *integrated enterprise* that effectively achieves process and personnel safety, environmental protection, and superior energy efficiency will realize faster time to market, lower total cost of ownership, excellent asset optimization, effective risk management, and economic excellence. These factors will determine the winners in U.S. manufacturing in the next decade.

<sup>1</sup> “Intelligent Systems: Architecture, Design, and Control”, A.M.Meystel, J.S.Albus, John Wiley & Sons, Inc., New York, 2002

# Innovations in Energy Measurement and Control for Manufacturing Systems

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## Abstract

*This white paper discusses the need for innovative technologies based on measurement and control to make manufacturing systems and equipment more energy efficient. Two objectives related to technology development are presented. The first is to obtain finer granularity in energy performance information from systems to improve current operations. Secondly, use such information along with lifecycle analysis to improve the energy efficiency of future designs for both systems and equipment.*

Numerous studies have reported that industrial energy usage represents approximately 30% of the total U.S. annual energy consumption. Reducing the level of energy consumption serves many interests related to national security, the environment, and the economy. Energy saving technologies have already been developed which according to some accounts offer U.S. industry the ability to save 10% in present operations. However, to meet ambitious national energy reduction goals for industry, further technological innovations are needed.

To identify and develop the requirements for such technologies, we need to first understand the detailed nature of energy consumption in manufacturing systems. Clearly, the measurement of electricity and of other utilities exists and is well understood. The utility metering of large areas of industrial operations provides an overall indication of gross energy usage, however, details of energy utilization of individual pieces of equipment is not easily obtained and in many cases does not even exist. As costs and regulatory pressures mount to achieve ever increasing levels of efficiency, energy consumption information at a finer granularity will need to be probed to identify demand patterns. Given such knowledge, appropriate strategies and technologies may then be more effectively deployed to address energy reduction opportunities. Also, as the capability to measure detailed energy utilization grows, insight into sub-system interactions will lead to further efficiency improvements.

Broadly speaking, there are three basic ways to reduce energy consumption. The first and most immediate deals with real-time control. In simple cases, control consists of simply turning a device or process on or off. In more complex processes, advanced multivariable control algorithms may be employed. The second approach is to modify or change some fundamental parameter or constraint of a manufacturing process so that a greater efficiency is achieved beyond real-time control. This approach requires more time as it may involve detailed engineering analysis, optimization, and validation before a redesigned process is commissioned. The third way to reduce energy has the longest time horizon since it involves the design of new energy efficient equipment. This last approach offers the greatest opportunity for achieving large energy savings because all currently available advances in technology may be integrated into the design of new equipment. Depending on the manufacturing industry, this opportunity may only occur infrequently so when the occasion arises, effort must be made to incorporate all existing knowledge into the design of higher efficiency systems and equipment.

For all of these three general approaches, information obtained about the system's energy performance behavior through detailed measurement of sub-systems and individual equipment can yield improvements in energy efficiency. For each of these paths to energy reduction, there are corresponding technical challenges and barriers which need to be overcome. It is here where advances in measurement methods and standards are particularly critical as a basic data and information infrastructure is needed to enable the desired improvements in energy efficiency.

For example, given that there is already throughput, cost, and quality data being collected, how should real-time energy data be acquired and integrated to provide a meaningful metric of system performance for effective energy-related decisions to be made? This question spans multiple domains resulting in the need to make correct tradeoffs to achieve energy savings and meet production objectives. Furthermore, since there will be a greater amount of data required to execute real-time monitoring and control of energy, naturally there will be additional costs to be borne by manufacturers. In some scenarios, it is quite plausible that deploying new measurement devices may be cost prohibitive and therefore implicit methods to determine energy consumption will need to be devised. The specification and subsequent development of low-cost, energy-aware sensors and actuators will need to occur simultaneously to allow for such pervasive monitoring and energy control. Also, standards for the design and deployment of optimal sensor networks for such "smart" energy devices will need to be in place for integration with higher level energy management systems.

Another challenge is the lack of integrated data between energy management systems and lower level processes. As an example, with high-level energy reporting, detection in the degradation of energy performance of individual processes is obscured by the large amount of aggregation in energy data which occurs. Therefore, meaningful hierarchical organization and aggregation of energy data is necessary to identify and isolate faults, leaks, or other process parameter fluctuations which result in poor energy efficiency. Measurement and diagnostics of the "health" of equipment and processes is a vital aspect of an efficiently performing system. Processes can only perform efficiently if they are maintained in a state of continuous calibration where drifts in set-points are prevented.

In addition to improving current operations, consideration must also be given to the performance of future systems and equipment. For this, lifecycle analysis which uses historical data having the fine resolution described above must be communicated to system and equipment designers alike. This data will permit designers to develop systems which can be more easily adjusted to reduce peak energy requirements and provide overall gains in average consumption. Furthermore, designers will not only have a better knowledge of expected energy efficiency, but will be able to better model and design the system to achieve even greater savings. Hybrid simulations which not only model discrete quantities such as throughput, cost, and quality but also incorporate continuous energy consumption profiles will undoubtedly improve the design and validation of energy-efficient manufacturing lines.

In conclusion, to obtain transformative changes in the energy consumption of manufacturing systems will require advances in all of the three approaches described. The foundation of detailed energy performance information which is both reliable and accurate rests on a core infrastructure of standards and measurement methods.



## Manufacturing and the Smart Grid

Today there is a growing emphasis on the environment and particularly on energy utilization. The main point being addressed here is the future of electrical power demand and the realization of a 'smart power grid.' As programs are being developed to address the makeup of a smart power grid, attention also needs to be placed on tools to assist in coping with changes in power consumption requirements when a smart grid poses a demand to change (lower) power usage. That is, the requirements to reduce ones draw on the grid to permit power to be allocated to a higher demand need.

One area that will potentially have to react to power demand changes is small- and mid-size manufacturing enterprises. Today, tools do not exist to aid a manufacturer in determining how to react to a power demand change. There are no smart tools to interface with the smart grid at the manufacturing shop level.

Some large companies are beginning to look at power consumption and are addressing it by monitoring the use of power at the equipment asset level. With this, it can be determined what assets consume what levels of power as they operate. In turn, it can then be determined which may need to be turned off to meet various demand needs. This method, however, is not necessarily the most efficient way to run an operation having to maintain a high level of asset utilization to maintain a profitable business. While it does provide a relative level of decision making capability, it does not carry the level of intelligence required to determine how to maximize asset utilization.

A better concept is to understand how various processes consume power during each segment of performing a task (e.g. a machining operation) to permit a change in the process to an alternate process plan. This approach will aid manufacturing engineers to develop process alternatives to produce product while maintaining a relative high utilization of plant resources. This methodology permits a company to optimize production to match power constraints.

This advanced type of decision capability does not exist today to permit "dynamic" production and process planning based upon power demands. To provide this capability, developments are required from various new enabling technologies. From technologies providing common data acquisition capabilities at the individual process level, to new applications and computing capabilities. The task being, the ability to match actual process steps to power usage and provide alternate process steps during low demand timeframes. If this is achieved, then various process recipes can be formed to meet varying power demands while maintaining sustainable production needs.

In the past this was not possible since data could not effectively be extracted from manufacturing equipment to make the necessary correlations to determine what steps consume what amount of power. Alternatively, to plan for executing certain manufacturing steps during low electrical demand intervals.

Recently a new standard has been developed, and is being further enhanced, to provide a common protocol and communication structure to acquire the necessary data to permit the linking of process steps to power usage. This standard is MTConnect<sup>SM</sup>. A royalty free open standard based upon Internet Protocol and XML language (refer to MTConnect.org web site for more information).

With the use of this standard, data can be collected or acquired by applications from discrete equipment, using standard networking technologies, to provide the necessary information to structure the above goal. This is the enabler to permit innovative technology developments that can be utilized in a myriad of ways to structure solutions to meet the future demands that will be placed on small- and mid-sized manufacturers by a ‘smart power grid.’

**Proposal 1:**

Develop software tools and applications that can assist small- and mid-sized manufacturers in addressing power requirements requested by a smart grid.

**Program Components:**

- 1) Develop products and components that permit the adjustment of process requirements based upon energy demand loads.
- 2) Provide resources to permit enhancements to the MTConnect open standard and tools to address new data requirements.
- 3) Investigate new computing technologies and concepts that may be utilized for implementation.
- 4) Additional software development incorporating “cloud computing” through internet connections and MTConnect data capture that also includes a customer’s power usage, rates, high/low demand time intervals and potential variability of dynamic electrical usage during manufacturing processes.

**Proposal 2:**

Develop and promulgate Energy Star criteria for “Industrial Machines” (a new category) for both U.S. machine tool builders and their customers. All benefits of the existing Energy Star Program would convey that currently exist. This effort would provide a competitive edge to manufacturers and users of U.S. machines while in parallel providing energy savings within the manufacturing sector.

**Program Components:**

- 1) Develop products, and components, that are themselves more energy efficient (Energy Star), and
- 2) Assist manufacturers and users in becoming more energy efficient with their own buildings and operations in preparation for “smart grid” connections.
- 3) “Industrial Machines” would become a separate and distinct category under the Energy Star Program coordinated with EPA and DOE.
- 4) Both the “Industrial Machine” manufacturer and the user of the “Industrial Machine” are tethered through a “smart grid” for measuring efficiency over an extended timeframe. Analysis via “cloud computing” will determine where and how additional efficiencies can be realized and improvements for greater energy savings.

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# Dual Manufacturing: Manufacturing Both Real and Virtual Products

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## Introduction

Product Lifecycle Management (PLM) is redefining the use of information throughout the product lifecycle and specifically, as discussed here, in the manufacturing phase of the product's lifecycle<sup>1</sup>. Product manufacturers need to consider manufacturing two products: the physical products that they have always produced and the virtual product that is the information about the physical product. This virtual product can provide manufacturers with a new source of value.

## Information Mirroring Model and Virtual Products

PLM depends on the conceptual idea of real and virtual products. Before the advent of computer systems that could handle the massive amounts of information about a product, the only practical way to have information about a product was to physically possess the product itself.

If a quality inspector wanted to check the dimensions on a batch of components, then the components were physically shipped to the inspector. (In many firms, inspection of the received product at the firm's site is still the primary quality control practice.) While blueprints were available on the "as-designed" component or product, "as-built" information on each instance of the component or product that was built from that design rarely, if ever, existed.

All products start out as virtual products. That is ideas and information about what the physical product should be. These virtual products are then realized in physical form through the manufacturing process. The manufacturing of products can be divided into three phases: making the first one, ramp-up, and making the rest.

"Making the first one" entailed getting a physical product that embodied the ideas of what the virtual product was required to accomplish. Ramp-up and production ("making the rest") relied on the premise that these products would be close enough to the first one so as to be functionally and physically equivalent. The accuracy of that premise varies widely even today, which is why expensive quality audit inspection processes are required of the actual product instances themselves.

Progressive manufacturing processes now capture data about the product as it is being manufactured so as to create not only integrated product and process traceability, but a virtual product model as the physical product is being built. As inspection processes become more technologically sophisticated and automated, the ability to create robust virtual representations of individual physical components and products becomes not only possible but also necessary.

These virtual representations form one of the components of the PLM Information Mirroring Model (Figure 1) and are a main element to allow Product Specification Management (PSM) to exist and perform a critical role in enabling quality as part of PLM. Product Specification Management consists of three components: the physical inspection hardware (gauges, CMM, scanners, etc.) to collect data as product is manufactured, middleware to take and organize this station-based manufacturing data and build a cohesive virtual products, and an Manufacturing Execution System (MES) to serve as a repository for this "as-built" virtual product.

## The Value of Virtual Products

There are a myriad number of uses that can be made of the virtual product created through PSM. In the manufacturing or build phase, the "as-built" virtual product is immediately available and can be transmitted to customers and other parties in the supply chain who need the information about the product to assure themselves that the product is actually being created to the required specifications.

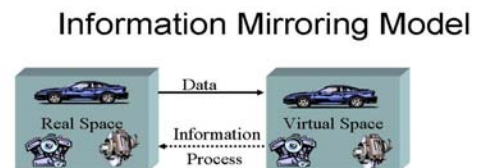


Figure 1

Unlike the physical product itself, the virtual product can be sent over large geographic areas instantaneously and can be sent to multiple locations simultaneously. As described elsewhere<sup>2</sup>, the new slogan of “transmit us the virtual product and we will then tell you whether or not to ship the physical product” may define a new paradigm in purchasing and manufacturing.

One automotive manufacturer has created a collaborative virtual space with its suppliers where the inspection of component parts at the supplier and later at the OEM is correlated down to the inspection point – though each may use different inspection methods and devices. The introduction of this collaborative model contributed to an 85% reduction in build issues in the subsequent model year as reported by the OEM.

In the create phase, the as-built virtual product can be used to validate the design of new, similar products. The data collected on actual results compared against specifications is invaluable in assessing manufacturing validity of new designs. By providing a feedback loop, the engineering / manufacturing divide can be bridged, reducing the slow iterative process of trial-and-error typically performed by manufacturing companies.<sup>3</sup>

For instance, while a specification and its associated tolerances may be manufacturable for the beginning of a production run, it may be that tool and die wear over a much larger run does not allow for those specifications to be met. Having the sequence of virtual products allows designers to understand either the requirement for different specifications or understand when new tool and/or die replacement is required.

At another automotive manufacturer, historical process capability information contained in the as-built virtual product of current and previous product models is being captured in the early design of new product models. This is in the form of dimensional tolerances that can realistically be expected to hold using similar manufacturing methods. In the absence of PSM technology, defining the proper tolerances in design for manufacturability (DfM) is a notoriously uncertain and difficult exercise, where the risk is that improperly assigned tolerances will lead to costly rework in design and tooling.

In the support phase, the issue of product liability often hinges on proving whether or not the individual product was manufactured to the required specifications. Without the ability to present data about the manufacture of a specific product, companies are at the mercy of plaintiff attorneys who raise doubt about the manufacturing process by asking “Isn’t it possible that the bolts holding my client’s seat were not tightened properly? Having the as-built virtual product, especially after the physical product may have been destroyed in an accident, gives the manufacturer protection against such an accusation.

Already, the US government has legislated detailed traceability at the level of individual product instances as a requirement on the F-35 JSF aircraft program, necessitating the implementation of PSM technology by the prime defense contractor and its suppliers. NASA has a one-hour informational demand in the event of an on-orbit anomaly for the Constellation project.

## Conclusion

We have only manufactured physical products in the past, because we could not manage the amount of data that virtual products need. The exponential advances in computer technology are making virtual products feasible. Virtual products, i.e. the information about the product, have a myriad of uses, not only in the manufacturing phase, but also throughout the product lifecycle. Product Specification Management as part of Product Lifecycle Management defines the components necessary to capture and organize manufacturing data into virtual products. Manufacturers need to consider moving from single manufacturing to dual manufacturing: manufacturing physical and virtual products.

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<sup>1</sup> See Grieves, *Product Lifecycle Management: Driving the Next Generation of Lean Thinking* (McGraw-Hill, 2006)

<sup>2</sup> See Dr. Michael Grieves, *MES: Achieving Real Quality through Virtual Products*, 2008 Whitepaper

<sup>3</sup> See Dr. Michael Grieves, *Multiplying MES Value With PLM Integration*, 2007 Whitepaper

## Manufacturing Simulation: The Need for Standard Methodologies, Models, and Data Interfaces

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Simulation technology can provide a highly effective means for evaluating the design of a new manufacturing system or proposed modifications to existing systems. This technology can be especially useful in supporting agility, sustainability, supply chain integration, as well as the development of new advanced processes. Manufacturing simulations are often used as measurement tools that predict the behavior and performance of systems that have not yet been implemented, or to determine theoretical capabilities of existing systems. Simulations are essentially experiments. As defined in Jerry Banks Handbook of Simulation, a simulation is: “...*the imitation of the operation of a real-world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of that artificial history to draw inferences concerning the operational characteristics of the real system that is represented. Simulation is an indispensable problem-solving methodology for the solution of many real-world problems. Simulation is used to describe and analyze the behavior of a system, ask what-if questions about the real system, and aid in the design of real systems. Both existing and conceptual systems can be modeled with simulation.*”

Although the potential benefits of manufacturing simulations are significant, many problems still exist. For example, the development of individual simulations within industry is still often more of an art than a science. Simulation methodologies have not been standardized - the skills and experience of the simulation analyst may greatly affect the way a simulation that is developed, the type of model that is constructed, the time it takes to build the simulation, as well as the utility and correctness of the results. Another major problem, is the lack of standard models – with each new simulation study, models are often built from scratch, resulting in redundant development efforts and the possibility of introducing new modeling errors. Finally, the lack of standard data interfaces makes it costly and time-consuming to transfer data back and forth between other manufacturing information systems and simulations.

### **Key Drivers for Manufacturing Simulation R&D**

*Agility* – Wikipedia defines agile manufacturing as a term applied to an organization that has created the processes, tools, and training to enable it to respond quickly to customer needs and market changes while still controlling costs and quality. Although historically discrete event simulations have been focused on addressing a number of issues relating to agility, e.g., system performance, throughput, and operating costs, simulation technology does not currently meet all needs in this area. Its biggest shortfall is in the time and cost associated with developing the simulations themselves. Simulations may take months to develop and are often not built because manufacturing managers are looking for immediate answers. Solutions are needed to accelerate the modeling and simulation development process, as well as to insure the technical correctness of the simulations themselves.

*Sustainability* - Simulation technology has been a significant tool for improving manufacturing operations in the past; but its focus has been on lowering costs, improving productivity and quality, and reducing time to market for new products. Sustainable manufacturing includes the integration of processes, decision-making and the environmental concerns of an active industrial system to achieve economic growth, without destroying precious resources or the environment. Sustainability applies to the entire life cycle of a product. It involves selection of materials, extraction of those materials, manufacture of component parts, assembly methods, retailing, product use, recycling, recovery, and disposal. Changes will need to occur if simulation is to be applied successfully to sustainability. Manufacturers will need to focus on issues that they have not been concerned with before. Since there has not been a demand for simulation technology with sustainability features, simulation software vendors and analysts have not typically addressed these issues in the past.

*Supply Chain Integration* – To achieve supply chain integration, multiple enterprises often need to work cooperatively to deliver end products. Some examples of the functional elements of a supply chain may include component part and raw material suppliers, transportation networks, distributors, warehouses, final assembly plants, and retailers. Typically, some elements of a supply chain will cross enterprise boundaries. Simulation analysts building supply chain models may need to interact with peer analysts in other enterprises that use different simulators for their enterprises. Complete internal information on each supply chain element may not be available to the analyst due to proprietary issues. Major research issues that need to be addressed include the development of distributed supply chain simulations using different simulators as well as the exchange of information between these simulations, e.g., standard message formats and access to shared databases. Data specifications are needed to identify the types of information that will need to be exchanged between different suppliers models, manufacturing applications, and databases. Examples of data that needs to be shared includes orders; schedules; tooling, raw material, work-in-process (WIP), finished part inventory and tracking data; production capabilities and capacities; resource status and usage; reject and rework data.

Other research areas include the development of simulation integration infrastructures using Web services technology that will allow supply chain partners to connect simulations of their facilities over the Internet. To address production requirements, simulations will need to include technical solutions for modeling manufacturing supply chains at multiple levels. Web-based solutions could enable the integration of multiple simulations at the supply-chain, enterprise, plant, and shop-floor levels. Off-the-shelf solutions do not exist today.

*Advanced Manufacturing Processes* – Some of the issues associated with the development and implementation of new, advanced manufacturing processes includes process validation, process capability analysis, tolerance analysis, ergonomic analysis, and tool design. Simulations can support these activities through: the modeling of systems, the execution of manufacturing plans, programs; the use of statistical process control techniques to determine whether processes can be kept in control range; modeling the effects of tolerance stack up on overall tolerance budget for a product or machine setup configuration to determine the probability that an instance of the product will meet specifications; evaluation of ergonomic aspects of worker tasks for efficiency of operation, theoretical production rate, risk of injury, rest requirements; and the development of tool management plans, definition of standard tool sets, prediction of tool wear, etc. Although special purpose simulation tools have been commercially developed to support each of these areas, standard data interfaces that would enable the exchange of data between these tools is very limited.

### ***Need for the Development of New Simulation Standards***

*Need for Standard Methodologies* - Simulation case studies are conducted to analyze and improve the efficiency and effectiveness of manufacturing organizations, systems, and processes. A study essentially represents a methodology for solving specific problems and getting answers to specific questions. Studies often model some aspect of current operations and validate the effect of some hypothetical change(s) to those operations. The performance of current and proposed systems are evaluated according to some set of metrics. Simulation textbooks typically recommend that a ten to twelve step process be followed in a simulation study. The recommended approach usually involves the following steps: (1) problem formulation, (2) setting of objectives and overall project plan, (3) model conceptualization, (4) data collection, (5) model translation into computerized format, (6) code verification, (7) model validation, (8) design of experiments to be run, (9) production runs and analysis, (10) documentation and reporting, and (11) implementation. Unfortunately, this approach often leaves considerable work and possibly too much creative responsibility to the simulation analyst.

Each new simulation case study performed today probably repeats at least some work previously done by others. Case studies typically contain proprietary information that private companies do not want to share. For this reason, it is unlikely that most case studies will ever be seen outside of the company that commissioned them. How can the duplication of work be minimized? The development of standard templates for different types of case studies would be a step in the right direction. More work could be done to create case study templates that are generic but more problem-domain specific, e.g., scheduling, layout, and material handling.

Individual case studies should be able to be used as modular building blocks and templates to solve more complex manufacturing problems. Ideally, case study templates should be “atomic,” i.e., unique, indivisible, and non-overlapping. A rigorous analysis should be used to ensure that each case study forms a clean, basic building block. The analysis should aim to assign any specific objective or question type to only one type of case study. A major reason for this rule is to avoid the infinite proliferation of custom-defined case studies. Repositories would need to be established for the case study templates so that they could be readily accessed by simulation analysts and software developers. Resources in the academic, research, and standards communities could be applied to this problem, thus avoiding the proprietary information content issues.

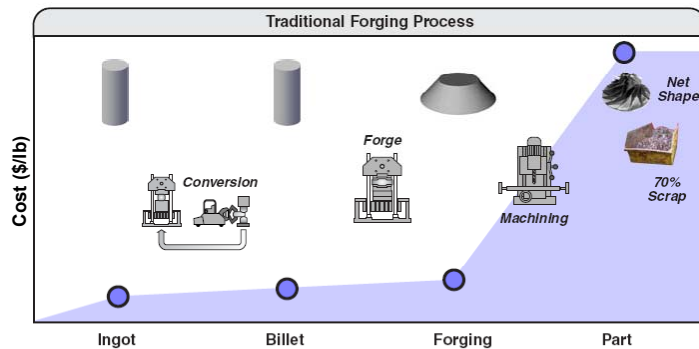
*Need for Standard Models* - Neutral model formats would help enlarge the market for simulation models and make their development a more viable business enterprise. Model libraries could be marketed as stand-alone products or distributed as shareware. Standard formats for models would make it possible for simulation developers to sell model libraries much the same way clip art libraries are sold for graphics software packages today. Simulation model libraries could be expected to increase the value of manufacturing simulators for industrial users much the same way graphics libraries increase the value of photo processing, paint, and graphics illustration software packages to their users.

*Need for Standard Data Interfaces* - The development of neutral, vendor-independent data formats for storing simulation data could greatly improve the accessibility of simulation technology to industry by enabling the development of reusable models. Such neutral, simulation-model formats would enable the development of reusable models and reference data by individual companies, simulation vendors, equipment and resource manufacturers, consultants, and service providers. Reference data sets to support sustainability could also be developed to provide information on energy consumption, alternative processes and materials, pollution data, improved equipment capabilities, worker task analysis, job satisfaction evaluation criteria, material recycling and recovery opportunities, community impact, mitigation strategies, etc. Standard message formats are needed to facilitate the exchange of information between simulations built by different organizations within supply chains.

# Challenges in Net-Shape Manufacturing of Metallic Parts

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Manufacturing of metallic parts can be accomplished by a large variety of processes including casting, forging, machining, powder processing, welding and countless others. Intrinsic to all of these processes is the desire to achieve a final in-service geometry – with requisite material properties – at the lowest possible cost. A typical cost flow analysis shows that cost quickly compounds late in the processing sequence. For example, in the processing and machining of a forged part shown in the figure to the right, the machining step (often viewed as an inexpensive process) actually adds significant cost because of the value of the metal removed and scrapped. If upstream processes to achieve *net- or near-net shapes* were fully developed, machining losses would be reduced to an insignificant level and the overall part cost would be far lower. However, **achieving net shape early in processing is an elusive goal.**



The benefits of net shape processing to the US manufacturing infrastructure is clear in the reduction of wasted material and machining costs. Additional benefits include reductions in the energy and greenhouse gas emissions associated with production, transportation, and recycling of wasted metal. Such reductions would impact material sustainability and availability for high-tech manufacturing, and provide a competitive advantage for US manufacturers. Modern net-shape processes include the traditional (e.g., investment casting) as well as emerging (e.g., laser additive methods, isothermal forging, powder metallurgy) technologies. In addition to improved material utilization, many of these processes provide an opportunity to introduce technological and practical advances, such as location-specific properties, lean manufacturing cycles, and inventory reduction. However, the full benefits of the processes have not been exploited because of economical and technical challenges. Cost is a key driver, and cost is driven by process rate, yield, raw material cost, capital cost, repeatability and flexibility. Many of the technical challenges are similar to those faced by the established processes: microstructural defects, shape retention, equipment capabilities, etc.

## Net-Shape Deformation Processes

It may seem obvious from the plot above that achieving near-net shape from a forging can reduce the machining cost. This is true, but forging press capacity, die material strength, and workpiece plasticity impose practical limitations that have not been overcome. Improvements in ingot and billet material that enable net shape forging can have a large impact. Superplastic forming, for example, has been commercialized for a few sheet metal applications, but shows promise for bulk deformation as well. Required developments include thermomechanical processing for producing superplastic billets, alloy design methodologies for meeting property requirements for both service and processing, (alloy developments to date have concentrated on in-service material property requirements, ignoring the processing limitations), and the development of advanced presses equipped with controls to forge to net-shape.

## Material Additive Processes

Material additive processes include laser-net-shape manufacturing, direct metal laser sintering, plasma transferred arc and electron-beam free form fabrication. They typically require expensive metal powder or

wire as a raw material. Despite the high cost of raw material, these processes find niches in manufacturing where local additions of expensive metal is more economical than removing a large amount of less expensive metal from an over-sized workpiece. Where small numbers of parts are required, the additive processes obviate the need for expensive tooling, thus becoming economically favorable. Tailoring properties by tailoring chemical composition to the local requirements such as corrosion resistance, wear resistance, chemical resistance and hydrophobicity seems to be an obvious benefit of these processes, but this advantage has not been largely exploited. The largest obstacle these processes face is the presence of microstructural defects (e.g., voids, impurities, or inclusions) in the final product; such defects can lead to catastrophic failure. Developments in process monitoring and control with in situ defect detection and remediation could reduce or eliminate the cracks, inclusions, and pores between deposit layers.

## Joining

The advent of high brightness lasers makes it possible to weld thick gauge materials commonly seen in numerous industries including windmill towers, locomotives, and pipe. These high brightness lasers enable the welding of materials that are up to 1 inch thick in a single pass. This is significant. Utilizing today's technology (e.g., metal inert gas or submerged arc welding) requires a "weld prep" where metal is removed and scrapped, then *replaced* with weld metal filler wire. The ability to weld 1-inch plates in a single pass can lead to a 90% reduction in both energy consumed and CO<sub>2</sub> emissions during the manufacturing process. For the heavy industrial manufacturing sector in the United States, this amounts to a reduction of  $2.98 \times 10^9$  kWh/yr. Combined with technologies that reduce the forging envelope, research in advanced joining will provide additional opportunity to introduce net shape manufacturing into the supply chain.

## Advanced Machining

Several new machining techniques that combine electrical, chemical and mechanical removal of material are emerging with the goal of increased throughput. These techniques apply lower mechanical loads, leading to lower capital equipment costs due to reduced machine stiffness requirements. They enable cost-effective machining of high-performance materials that prove difficult or impossible to machine conventionally. Environmental stewardship adds a burden to these new technologies, requiring process developments.

In line monitoring of the output of high-throughput machining centers is required to ensure that the product consistently meets geometric tolerances. However, conventional gauging and tooling is expensive and inflexible. High-speed, general-purpose, non-contact measuring systems could detect tool wear or alignment issues, allowing corrective actions to center products within customer tolerances.

A review of the balance sheet of a typical machining center indicates that approximately 10% of income results from the sale of machining chips and scrap metal. As this amount represents the typical net income of such a center, the chips and scrap must be viewed as a *product* rather than waste. High speed detection and sorting of chips by alloy composition can add significant value. Reclamation of machining waste in electrochemical machining processes should be addressed.

## Recommendations

While there has been impressive fundamental work in some of the above areas to develop new technologies, they have not been widely implemented. In some cases this is because of high initial investment. In other cases, new design practices to take advantage of new materials have not been established. The key areas in R&D needed to overcome the challenges of net shape manufacturing should include:

- Development of new manufacturing technologies for net shape manufacturing
- Enhancing current net shape manufacturing technologies
- Modeling & simulation of net shape manufacturing processes
- Developing design practices capable of taking advantage of the new technologies
- Devising approaches for process control that incorporate in-line monitoring and adaptive control



## **The Future of Advanced Alloy Manufacturing: Material Modeling**

Advanced alloy development is an active area of research with pervasive impact on the United States' manufacturing industry; indeed airframe, jet engine, power generation, medical device, defense, and automotive companies all stand to benefit from such research. We need to avoid time-consuming traditional methods of development and access state-of-the-art micromechanical modeling techniques that accelerate the development of these alloys and sustain our country's global competitiveness. Unfortunately, a disconnect currently exists between alloy developers and the manufacturing base of industries that want to machine components utilizing new alloys. Time-to-market advantages are being lost while our manufacturing base struggles with machinability issues that accompany new, unfamiliar alloys. Additionally, new alloys are inhibited from broad-based dissemination due to prohibitive manufacturing costs.

Computational alloy design is an emerging approach to new alloy development that relies on mechanistic and predictive material models. By working with the end-user of an alloy, the final microstructure is optimized for the best combination of relevant properties. During the computational alloy design process, structure-property models dictate optimal microstructure to achieve the desired properties; in turn, process-structure models dictate optimal processing to achieve the targeted microstructure. In the last decade, such physics-based material modeling has proven to be an effective method for reducing new process costs and accelerating process implementation.

We now need to fill the void of structure-property models relevant to machinability using a combination of computational alloy design expertise and machining simulation leadership. Current computational performance levels often impede rapid tooling and process development, but these tools can be expanded and leveraged using advanced machining simulations to incorporate both alloy performance and manufacturability into a concurrent engineering framework for high performance alloys. By focusing on relevant microstructural features and their impact on properties that drive machinability, the United States can leverage the same process-structure models utilized in alloy design to develop an annealing cycle that achieves targeted microstructures. For example, it may be possible to design a titanium alloy annealing cycle that accesses a morphology of coarse alpha particles otherwise undesirable for material toughness, while being compatible with a subsequent final heat treatment to restore the properties of the final product.

It is time for the manufacturing community to adopt integrated multiscale physics-based predictive modeling for the development of machinable advanced alloys and corresponding component machining processes. By incorporating micromechanical constitutive models from alloy development models into physics-based machining models, manufacturers will gain detailed microstructural information about new machined components. In addition, outputs from physics-based machining models will also serve as a machinability feedback loop during alloy development, enabling developers to improve alloy machinability in the development stage while maintaining high performance design properties.



Technology is the wave of the future, and an industry driver for the United States' emergence as the leader in developing advanced alloys both affordably and time-efficiently. The task is complex – finite element modeling must account for geometric, tooling, speed, feed, and other extrinsic machinability factors using validated experimental techniques – but not unfeasible. The reward will be simulation accuracy that provides insights to intrinsic material properties that influence machinability. The end result is a substantially more productive, more competitive U.S. machining sector, generating high profits and providing products to market much faster – particularly components made from advanced alloys. It's time to start machining smarter.

## 21st Century Methods for Composite Processing

Thomas Rose: Advanced Processing Technology, Norman OK, 73071, Ph405-360-4848

Energy is a critical to the economy of the US. Composite materials address many of the energy issues both to produce energy in products such as windmills and to save energy in products such as car bodies and aircraft. There is also a need to update infrastructure to retain and regain jobs in the USA.

By 2010, the global market for Carbon Fiber Reinforced Plastic (CFRP) composite materials is predicted to be worth \$13.6 billion, representing a huge increase of 37% over 2006. CFRP also has a role as a replacement for metals in infrastructure. Corrosion of metallic structures has a significant impact on the U.S. economy. In a congressional study, the total economic impact of corrosion and corrosion control applications was estimated to be \$276 billion annually, or 3.1 percent of the U.S. gross domestic product (GDP). 2 Estimates for the DoD alone are between 10-20 Billion.

While the use of composites has grown, many of the manufacturing and repair processes have remained stagnant. There is a large and growing need to update the underlying technology to take advantage of new tools developed over the past forty years. Hundreds of millions of dollars are wasted each year using specifications and practices that had their genesis in the 1950's and 1960's.

The need to update these specifications and practices has a significant relevance to retaining jobs and advancing both defense and commercial industry within the United States.

**Background and Approach:** Current specifications for composite materials were developed before it was possible to measure material properties during manufacture so the approach was to use the same material and process them the same way every time. The integrity of this practice relies on a "no change" policy.

Stated another way, any change in the process is unacceptable because its effect on the performance of the material is unknown. The objective of this white paper is to increase the visibility of properties critical to performance during the process and thus enable far greater range of acceptability. This enables many more opportunities for cost reduction and performance improvement.

Fundamental to all process improvement is the ability to link material properties to performance and then optimize around those properties. The improvements in computers, cure models, communication, instruments and sensors combine to make it possible to measure and link material properties to process actions with far greater accuracy that was available in the past.

The benefits range from salvaging a bicycle part that might otherwise be scrapped, to the ability to build a complex bridge or sophisticated weapon that would be impossible using the legacy technology.

Modern Laboratory 1970



2008



Challenge: The barriers to change are high. Success requires new infrastructure. There is no requirement for change to infrastructure without a specified requirement. The catch 22 is that specifications cannot change without data and without a change to the infrastructure one cannot gather the data.

By leveraging the knowledge gained from past processing science programs<sup>4</sup> and substitution methodology projects<sup>5</sup> and by using new instruments, computers and data management systems, an infrastructure can now be developed with the final goal of new specifications for manufacturing.

**Goals:** The near term goal is to adapt instruments, equipment and software to create processing alternatives. During this phase the goal is more efficient and accurate methods evaluate materials, address production problems and improve manufacturing methods within the limits of existing specifications.

The basic components to support the MSM approach have been installed and multiple milestones have been achieved.

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- Instruments to measure state of prepreg during cure with linkage to controls.
- Cure models that can be validated using low cost in process methods
- Microwire sensors to determine temperatures deep within a laminate
- Linkage of models and microwires for cure modeling
- Remote link of process equipment to lab instruments
- Real time and post process determination of visco-elastic state

These technologies are ready to be tested and evaluated in manufacturing and, if properly supported, will provide durable jobs based on a domestic infrastructure. Many of these improvements can be targeted to applications such as bridges, and buildings whose jobs cannot be relocated.

This will require a multiyear effort within the framework of a collaborative effort with industry, academia, and government. This work is still developmental and is expected to include failures and successes as the balance between sophistication and shop friendliness evolves. In the end such an approach will inevitably lead to major cost savings and performance improvements.

AvPro has worked in collaboration with large (GKN, Spirit Aerosystems, Rockwell Automation Roper), small (Thermal Solutions, Helicomb, First Wave) universities (Wichita State, Oklahoma University, UCLA) and others to demonstrate proof of concept and lay the foundation. Much work needs to be done that can only be achieved with additional resources and beyond the scope of AvPro and much of which must ultimately reside in the public domain and therefore has limited potential for attracting private capital.

Much of AvPro's work has been within the aerospace community: thus emphasis on the catch 22 regarding specifications. However a similar catch 22 exists in the commercial world that is less defined and therefore a greater challenge. If it has not been done before and does not have an immediate ROI tied to a tangible product, venture money is extremely difficult to obtain. Thus truly innovative ideas that derive their utility from an existing infrastructure will not be funded until the infrastructure is in place but the infrastructure requires products, the development of which venture money will not fund.

In summary: there is a significant opportunity to lead in many areas of composite processing if the tools to support it are developed. Personnel directly responsible for materials and processes from both the public and private sector support the concept. Funding of a team with the proper vision and capability with resources to move from proof of concept done "below the radar" to a program large enough to instantiate change has not been available.

Many of the key drivers for this technology are the establishment of (a.) new methods based on (b.) new instruments that require (c.) data to determine repeatability, reproducibility of results and (d.) methods and standards to validate and substantiate the accuracy and precision of the results.

# Product Tolerance Representation: Critical Requirements for Product/Process Interoperability

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Daniel A. Campbell, Software Director, MetroSage, LLC

The “perfectly nominal” part is an ideal never fully achieved in manufacturing; however industry can fabricate parts that fit and function when acceptable limits from tolerances are introduced. Therefore a critical responsibility of a designer is to define product acceptability by augmenting the nominal geometric shape with the appropriate set of tolerances. Within the past 60 years, we have seen the refinement and standardization of tolerance representation which, when implemented properly, control the location, orientation, form, and/or size of part features in a complete and unambiguous manner.

**Statement of the Problem:** Current *electronic* product definition systems (i.e., CAD Systems) represent completely and unambiguously *only a segment* of the product's design. Product tolerance presentations are generally of the form of mere textual annotations, devoid of any meaningful association to the product geometry. This gravely limits the designer's ability to efficiently create and communicate complete and unambiguous tolerance information, and it cripples downstream applications that depend on such information.

**What is Needed:** A full semantic representation of 3-D geometric dimensioning and tolerancing (GD&T), within or tightly coupled to the product definition system.

Meeting the stated need in an adequate manner will require software capable of:

- Augmenting a solid shape with tolerance definitions
- Implementing the notion of tolerance features (collections of one or more topological faces)
- Representing tolerances semantically (not just as annotations)
  - Dimensional / coordinate tolerances
  - Geometric tolerances
  - Specifications (e.g., thread specifications.)
  - General property attributes (e.g., notes, markings, cosmetics)
- Designating functionally important tolerance features as functional datum features
- Building datum reference frames (DRFs) from datum features
- Associating DRFs to appropriate tolerances
- Assigning tolerances to appropriate tolerance features
- Recognizing tolerance features automatically and interactively
- Inferring correct tolerances automatically
  - Per ANSI Y14.5
  - Per company standards
- Checking, validating, and scoring a piece-part's functional tolerance definition
  - Are all geometric faces assigned to tolerance features?
  - Are all tolerance features properly constrained for location, orientation, size and form?
  - Are there any unused DRFs?
- Publishing application programmers' interface (API) suite
  - Extending tolerance analysis
  - Supporting downstream applications (e.g., inspection)
- Exchanging tolerance definition to other product definition systems

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<sup>1</sup> The Kansas City Plant is operated and managed by Honeywell Federal Manufacturing & Technologies, LLC, for the NNSA

## The Key Driver: Efficient and Economic Manufacturing

Tolerancing is an important aspect of design, plus the cost of correcting design errors during the design process is relatively low. Intelligent automated tolerancing capabilities and, in particular, the ability to independently check that a part's tolerance definition is correct, complete and unambiguous, will ensure that tolerance errors are caught early in the product development cycle.

Having validated tolerance information as an integral part of product definition means that, with suitable interoperability, the same validated information can be used in downstream applications, such as measurement process planning, measurement results analysis, assembly analysis, CMM part program generation, etc.

## A Case in Point: Intelligent, Automated, Economically Optimized Inspection Process Planning

An important aspect of measurement planning is to ensure that the measurement devices and procedures to be employed are adequate for the precision required in the ensuing measurements. Another is to ensure that the measurements are carried out in an economically efficient manner, making optimal use of the measurement resources available. In inspection operations the precision of the measurements bears heavily on accept/reject decisions and can play a critical role in the risks of Type I and Type II errors, each of which has its own attendant economic consequences. Recent years have seen noteworthy advances in the theory of risk and cost analysis. National and international standards have addressed these concepts as well. Moreover, new software products now offer well validated estimates of measurement uncertainties *via* science-based modeling and simulation. Thus the essential theory and many component technologies exist for the implementation of an intelligent automated inspection process planning system, a software tool for use by the manufacturing community to enable the automated production of design-based measurement strategies of *known reliability* and *high economic efficiency*. Manufacturers using such a tool would find that they (1) could dramatically speed the production of measurement strategies for new or existing parts; (2) would know the reliability of these strategies; and (3) would know (based on their own assessment of cost functions for measurement, the costs of accepting a defective component or rejecting a good one) the economic consequences of each alternative strategy. Such capabilities offer the prospect of significant advances in profitability and product reliability.

With all that said, the problem stated at the outset of this document remains. Under current conditions, the potential user of such a system would not have ready access from the design system to validated tolerance information tightly linked to the part geometry. This presents an obstacle to what could otherwise provide a significant advance in manufacturing.



***“Yeah we’ve got a tolerance problem alright, it’s that we do not have a correct, tested, complete & unambiguous tolerance representation in our CAD systems and therefore we cannot use it for downstream applications and accurately exchange it”***

# Information models for machining interoperability, optimization, and simulation

*Martin Hardwick*

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*President STEP Tools, Inc.*

Today, Computerized Numerically Controlled (CNC) machines are programmed using Computer Aided Manufacturing (CAM) systems that receive their input from Computer Aided Design (CAD) systems. The CAD systems are used to define the nominal geometry and required final dimensions and tolerances of a part. The CAM systems are used to define processes that will make the part by adding material to, or more commonly removing material from, a workpiece.

The input to a CAM system is a drawing or its equivalent and the output is a set of G-codes (Gerber plotter codes) that tell a machine tool how to move its components in a sequence. If the machine is setup correctly then executing these codes will reveal the part. The antiquated G-code language is now being replaced with a modern associative language that makes CNC programming more visual and easier to control. It builds on the STEP language that is implemented by nearly every CAD system. FANUC, the leading vendor of CNC controls, recently demonstrated a hybrid control that machines a part from a STEP-NC description. The figure below shows the data that was machined.

STEP Tools and an industry team of aerospace and heavy equipment manufacturers are testing STEP-NC and extending its capabilities to enable cooperative process planning and simulation by teams of suppliers. The extensions include:

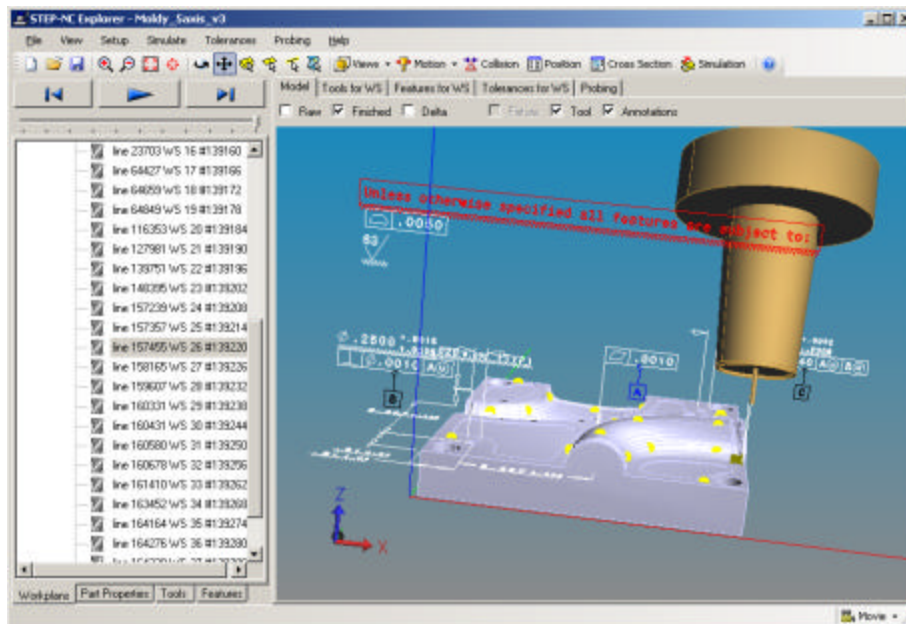
- Definitions to speed up or slow down a program in response to changes in the production schedule. The aerospace industry has estimated that the average time for a machining job can be reduced by 15% or more if the process can be fine tuned in this way.
- Definitions to enable networked simulation so that a contractor can ask a team of suppliers to plan and simulate the manufacture of a part on multiple machines, at multiple locations and in multiple stages.
- Definitions to allow changes to the tooling so that an operator can make adjustments to a program received from a supplier without having to ask a CAM programmer to make a complete new program from the original drawing.
- Definitions to enable energy consumption estimates so that an enterprise can minimize the energy required to make a part by selecting the most appropriate machines and tooling.

- Definitions to adjust the machining programs using the results of measurements so that the form of a part can be adjusted to meet the current dimensions of a large assembly.

The mathematics required for these capabilities is mostly defined in the literature. The STEP-Manufacturing team is assembling an infrastructure that allows these definitions to be harvested in an open, shared framework defined by standards.

A new modeling method, called a Usage Guide, is being developed to add onto the STEP standards for the new semantics. The first Usage Guide showed how gears can be represented as AP-214 data. STEP-Manufacturing is developing a Usage Guide to describe the kinematics of machine tools in AP-214. Concepts first developed for ontologies are being used to enable **Dynamic Usage Guides** that can be customized to the requirements of specific machines and operations. Examples include the operations specific to a particular CAM system, and the program cycles specific to a particular machine tool.

The new STEP-NC programs are a shared resource that can be stored in appropriate media. The new programs can be edited and linked using software tools such as the STEP-NC Explorer illustrated below. Simulators are used to check the consistency of the programs. Engineers like to solve technical challenges but do not like to waste time because of antiquated methods such as Gcodes. By making CNC programming more accessible, STEP-NC allows more innovative products to be developed more quickly. The definitions described here add new functionality to the standard so that the new products can be made faster and more cost effectively.



*STEP-NC Part machined by Fanuc at Boeing Renton Plant on 7.14.2009.*



## **Personalized Production Paradigm**

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**How can we sustain a strong auto industry in the US?**

**How can we create new Small Business industries?**

**How can we create new manufacturing jobs?**

Our proposed personalized production of automobile interiors will boost the US economy, and create new jobs and new industries. Instead of compromising on an interior design offered by the auto manufacturer, buyers will be able to design their new car interiors to meet their needs: Starting from an open interior space and filling it with available modules.

Automobile interior modules may include, computer stations, storage boxes, microwaves, refrigerators, beds, dog baskets, folding tables, clothing racks, and portable-potties for kids, etc. We are proposing an open-architecture structure for all these mechanical components, parallel to the i-Phone and PC electro-type open architecture software.

When this approach is adopted by the auto industry and mechanical-electrical open-architecture standards are established, dozens of small new companies will start to produce special modules (such as dog baskets and storage cabinets), which will evolve to several new industries. In addition to trading used cars, people will trade used modules as their needs change and they want to update and remodel their existing cars. Because this personalized production business model is beneficiary to both the manufacturers (that are being paid before the product is built) and to the customers (who are getting exactly the product that they need), and because it will generate new industries that produce innovative modules, it could be a giant booster to the US economy.

The main engineering research challenges are

1. Creating a new-generation of CAD based systems by which buyers, who are not necessarily engineers, could easily design their car interiors; it will apply control feedback principles, which will aid buyers to converge to arrive at their desired products.
2. Creating a new-generation of assembly systems that will be able to handle thousands of options, and still produce cars at mass-production cost.

The main practical challenges are defining the regulations and standards for mechanical interfaces that will guarantee safety, as well as defining the standards for electrical and information interfaces. NIST should take a leading role and work with General Motors, Ford and Toyota on establishing these standards.



## **Ushering in the Next Generation of Factory Robotics & Automation**

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The manufacturing capability and sustainability of the U.S. industry has been losing ground to its Asian and European competitors for the last few decades. For example, Japanese and German companies currently dominate the market of industrial Robotics and Automation (R&A) solutions with the support of low price Chinese manufacturers. Given the high labor cost in North American markets, the only viable option for U.S. industries to compete with a global market is via state-of-the-art R&A. Furthermore, most capital-intensive and wealth producing industries in the U.S. neither have the technical expertise nor the manufacturing capability to survive without cost effective R&A, which places these industries in a precarious state of vulnerability to disruptive technologies that may redefine the value stream map of their respective businesses.

The unfortunate reality is that the domestic production of consumer products using conventional processes could soon cease to exist based on a 30-year track record of global outsourcing pressure toward regions with low labor and investment costs. The transformational development and establishment of next generation manufacturing assembly processes using the latest in dexterous and intelligent robotics and lean production technologies will provide the necessary competitive edge for a variety of affordable products for the future. As a result, jobs will be retained as some will shift from line work to technical support and operation of the robotic systems.

The structured environment existent in current production facilities that enables robots to perform their tasks actually limits flexibility and drives a significant cost penalty for using robots. There has been some progress in enabling robots to operate in manufacturing operations with less structure, but robot capability in this area is very limited. This “robot capability gap” persists and limits the range of applications and business conditions under which robotics provide a feasible commercial alternative to other means of implementing manufacturing processes. This gap is especially evident in the automobile industry when examining the final assembly process.

From an end user perspective, we believe that a new generation of assembly automation can be anticipated to significantly reduce the reliance on fixturing, mechanized structuring, and conventional sense-plan-act programming. This capability would enable assembly automation with a set of little or no more infrastructure requirements than a completely manual process would. These new assembly processes will exploit the existence of a flexible robot perception system as an integral component of a three-part strategy that includes: 1) highly flexible robots/end effectors, 2) flexible perception, and 3) safe integration/harmony with people, which are also performing tasks in the assembly process. The cognitive component of the perception system would facilitate the “assignment” of the automation to a set of assembly tasks and/or assistance to others performing a task not yet appropriate for automation. This capability will also enable the rapid “reassignment” of the automation to other tasks as required by production mix and business needs. Many U.S. manufacturing domains stand to benefit from the flexibility and productivity that this form of dynamic automation brings to the assembly process. Multi-purpose robots that can

safely collaborate with human workers will elevate the capabilities of existing assembly workers in the pursuit of providing quality products to end-users.

A key factor in creation and adoption of the next generation manufacturing technologies is the development of flexible perception and human-like control technologies. In addition, by taking a leadership role in the development and adoption of such emerging technologies, we could ensure that the jobs created in this new area stay in the U.S. These jobs can only be created and retained if a technological edge can be found that overcomes the attraction to low-cost labor regions. Through the pervasive use of intelligent R&A that can be as flexible and as easily trained as people, related industry jobs could also be moved from offshore to the U.S. as a direct result of this new technical capability.

Our goal is to see revolutionary advancements in dexterous robotics leveraged in a new energy efficient automation environment that combines the best possible mix of human and machine capabilities. These next generation robots include “safe robot” technologies that allow the seamless integration of people and dexterous robots in one lean process. The key factor for the success of this approach is that the new systems leverage the infrastructure and flexible material processes that traditional manual systems use rather than expensive and traditionally inefficient automation methods. This substitution enables a substantial reduction in R&A support investment that can normally be up to 10 times the cost of the robot themselves.

From a scientific point of view, this endeavor encompasses a wide range of disciplines. Even when current commoditized hardware capabilities are almost at the level required to enable us to cross the capability gap, the actual integrated control and communications software systems are still lagging due to the heavy burden of current legacy systems. The historical paradigm for controlling R&A systems relies upon the system designer being able to specify a priori every requirement and possible condition of the system. This approach leaves no room for changing conditions, adaptability, plasticity, and in general, learning.

One of the main hindrances that is currently preventing the evolution of the next generation R&A is the lack of standards of performance and test methods. Every R&A manufacturer attempts to keep their customer base captive by having closed and mostly incompatible systems. Most of the major specifications of these systems are given in terms of mechanical or electrical characteristics rather than in terms of overall system performance. NIST could play a vital role in advent of the new wave of R&A technologies by facilitating the dialog among interested parties and establishing both system standards and evaluation metrics in order to be able to track the level of capability improvement of such systems. Such specifications should not only encompass hardware and software metrology targets, but also high-level system qualitative and quantitative capability measurements for standardized processes. In a way, this will enable an R&A revolution equivalent to the one observed on the computer industry in the mid 1980's. Effects of this achievement will be reflected deep into the fabric of industry and ultimately into the entire society; but in this case instead of putting a computer in every home or pocket, it will enable the pervasive use of functional R&A in all areas of our daily lives, from the factory plant floor to even your kitchen floor.

We predicate that there is a unique opportunity to make progress in this arena by harnessing collaborations between industry and academia. Our existing collaboration between Georgia Tech and General Motors is one such good example. In our collaborative efforts to bring cutting-edge R&A technology from the labs to the factory floor, we are forced to reconcile some of the real issues involved with integrating flexible R&A with existing manufacturing processes and to focus on technologies that deliver real value added to the end customer.

## **Key Barriers to Rampant Random Bin Picking Retrofit Deployment**

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With an estimated 1,000,000 robots deployed by the end of 2010 the increasing requirement for Advanced Sensor Retrofits to deployed Robotic Workstations is expected to continue to increase. Retrofit solutions have always made good sense for complex substantial installations for discrete and continuous process manufacturing. The barriers however have remained the same throughout the years: controller interface, sensor compatibility, solution engineering and systems integration. Issues such as these become real barriers for complex applications such as Random Bin Picking

There is little doubt that Random Bin Picking (RBP) is a significant advanced manufacturing technology innovation. The key industry drivers for RBP include cost of manual operations, difficulty in material handling, and hazardous conditions. However the key drivers for Retrofitting are different; cycle time, error rates, down time and recovery processes. A common set of enablers to Robotic Retrofit experience would at the same time enhance additional innovations. We believe these enablers would also span multiple manufacturing sectors and would be of particular interest to the baseline infrastructural technology areas including measurements, performance metrics, test methods, and standards.

Reasons to deploy advanced manufacturing technology innovations include: sustainability, flexibility, agility, reconfigurability, additive manufacturing, lifecycle information exchange and management, science-based modeling and simulation, intelligence and optimization of manufacturing systems, high throughput, high-accuracy measurement technologies, automation and robotics with increased pace of innovation. A good robotic retrofit candidate will naturally address many of these points. A good random bin picking solution will focus on solving some of the more complex issues for manufacturing such as: flexibility, agility, and reconfiguration. However, critical factors that are harder to achieve and that remain barriers to deployment are, front end engineering in order to complete deployment, sustainable high throughput, rapidly deployable enhancements and innovations.

The front end application engineering includes: part programming, path planning, end effector design and build, sensor and controller integration and then the systems engineering to make the operation function as intended. We believe addressing all these front end technical barriers will dramatically improve the successful update of aging robotic deployments. It has been our experience just this year with a body assembly line in Ohio, that after the pain and agony of the “front end” the end result was beyond the customers expectation, in fact our retrofit of vision guidance to a 10 year old robot brought the solution beyond the original systems capability. However the weeks taken to get there were very costly.

“What are key drivers for advanced manufacturing technology innovation?”

1) We see a need for a new Vision Guidance Controller Architecture. With open standards that supports things like additive manufacturing, where vision guidance for example can also provide product quality and process validation. Higher speed device communication is critical to meeting throughput requirements. A more open solution would allow wider variety of sensors that could improve the accuracy as well.

2) We see a need for modeling and simulation research where standards for object representation and solid model exchange could enhance the use of dynamic simulation. Simulation when uses effectively can help prevent engineering errors and solution gaps, however the pain and cost to produce effective simulations remain too high for routine everyday use. A simple pick and place dynamic simulation with complete robot model data still takes several days to complete in the most crude representation.

“What are the most important areas where R&D is needed (particularly in measurement and standards) to overcome barriers and accelerate manufacturing technology innovation?”

1) We think an Adaptive Guidance Open Architecture standard could be a focus area that with Defense support and Manufacturing’s requirements could produce a serious dual use opportunity. Such an open standard would also allow a large body of research to produce innovation at a much increased pace.

2) We also think Modeling and Simulation should be supported by a standards effort for information exchange as well as performance measurements. With strong simulation capable of emulating complex and complete intelligent automation systems designs could be validated before code is completed or machines are built. Performance enhancements could be identified and validated very early in the deployment cycle. Saving time and money for all involved.

Where is the next innovation?

- Real-time instant sensor and device calibration process eliminate lengthy manual calibration processes. Embed calibration data such as fixed focal length or camera model specific information.
- Real-time instant object pattern/feature learning, detection, orientation and inspection, How all this gets done is the challenge, once we are able to rapidly retrofit and deploy complex robotic solutions like random bin picking this is where we will turn our attention.
- 3D Models of objects, workstations, devices, parts, environment and with dynamic information to drive simulations. We need solutions that can be engineered more accurately, and faster with validation of results before fully executed or deployed.
- Bundled mechanical software solutions. In random bin picking we have found that the end effector is as complicated to design as the vision guidance application. Plus the need for the vision sensor to have clear FOV is becoming more and more an issue. We see two innovations in the horizon that can help rapidly deploy RBP and other advanced automation. 1) define a set or range of end effectors that are grouped by capability, flexibility, dexterity, power and pre-engineer them with universal wrist attachments base don a standard. 2) split the sensor positioning from the point of action, this means develop a robot arm just to position the lens, then maintain the muscle action to a separate arm that is able to maneuver into tight positions without a camera hanging off the wrist or having to move to an awkward location to get an image then relocate to pick the part.

## Sustainable Manufacturing

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After surveying thirty large corporations, a recent article in the Harvard Business Review declared that “there is no alternative to sustainable development”<sup>1</sup>. A parallel, more extensive study by MIT found that “there is a strong consensus that sustainability is having – and will continue to have – a material impact on how companies think and act”<sup>2</sup>. These dramatic developments owe to the fact that the manufacturing sector, represented by these companies, has a significant impact on the economy, society, and the environment around the world. Close to home, the U.S. manufacturing sector contributes 11% of the Gross Domestic Product (GDP) and provides 10% of the nation’s workforce with high-paying jobs. It is also the largest consumer of energy (45%), the second largest consumer of mined materials (21%), a major producer of solid waste (10 trillion kg per year), and a significant user of hazardous materials – all of which are implicated in a growing number of environmental problems. These facts are not lost on the U.S. government. The U.S. Department of Commerce (DOC) recently named sustainable manufacturing as one of its key performance goals and called upon NIST to provide national assistance to realize this goal.

Recognizing the environmental impact of manufacturing and the products they produce, many countries and regions have introduced regulations such as RoHS (Restriction of Hazardous Substances), REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) and WEEE (Waste from Electrical and Electronic Equipment) that restrict the sale of products containing hazardous or prohibited substances. Additionally, many companies have introduced consumer-oriented labeling to indicate various aspects of sustainability in their products, including Energy Star and labels for recycled content and recyclability of products. Some of these labeling are mandated by governmental regulations. Even if many of these regulations are local, their implications on the manufacturing sector are global – for example, the U.S. manufacturers are scrambling to comply with the European regulations because they do not want to be locked out of that lucrative market.

As the U.S. manufacturing sector sells globally, it also sources globally. It manages a global supply chain in all four major phases of a typical product’s life cycle: raw material selection, product realization, customer use, and material recovery. As the U.S. manufacturers and their global suppliers struggle with sustainability issues in the product life cycle, they are discovering that they need to measure, control, and manage sustainability in a complex mix of temporal (life cycle) and spatial (global supply chain) dimensions. Additionally, they have to respond to the impact of their actions on economical, social, and environmental issues in this complex space-time domain. Business executives often bemoan that “you are only as green as your supply chain”<sup>3</sup>, and compare the global sustainability challenges of today to the ‘total quality management’ (TQM) challenges they faced nearly a quarter century ago<sup>4</sup>. They are also concerned about the dwindling supply of raw materials and resources (e.g., energy, water), and the sometime unfriendly sources of material supply.

At a recent summit organized by the DOC Sustainable Manufacturing Initiative,

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<sup>1</sup>“Why sustainability is now the key driver of innovation”, Harvard Business Review, Sept. 2009, pp. 56-64.

<sup>2</sup> The business of sustainability, MIT Sloan Management Review Special Report, 2009.

<sup>3</sup> <http://www.hbrgreen.org/>

<sup>4</sup> “The green conversation”, Harvard Business Review, Sept. 2008, pp. 58-62.

representatives of a broad spectrum of U.S. industries expressed their frustration over a vast number of inadequately defined measures of sustainability, the difficulties with collecting and exchanging sustainability information, and difficulties with working across enterprise supply chains to ensure meaningful improvements in sustainability and conformance to regulations.

These concerns were echoed with greater technical depth and clarity in a Sustainable Manufacturing workshop hosted by NIST soon afterwards. The NIST workshop attracted participants from large and small companies in the U.S. manufacturing sector (GM, Ford, GE, Xerox, Lockheed Martin, Rockwell Automation, P&G, Siemens, Harbec Plastics, Masco, URS), software vendors (Dassault Systems, Siemens PLM, PTC), government (DOC, NIST, NASA, NSF), non-governmental organizations (WRI, NCMS, CAMDUS, ANSI, NACFAM, ASTM), and academia (Stanford, Purdue, Georgia Tech, RIT, U of Kentucky, Portland State U., Texas Tech).

Most of the industrial concerns and lessons learned were summarized in the industrial panel convened by the NIST Sustainable Manufacturing Workshop. Some of the messages were:

- Sustainability should start with leaders at the top. Also, bottom-up solutions are very useful and powerful (because people want to be part of the solution to an important problem).
- Educating suppliers on sustainability is important and is a challenge.
- Regulations drive a lot of engineering action – often, non-compliance is the fear that drives these actions.
- Branding is very important for business. Many companies are positioning themselves at the forefront of sustainability movement to protect and/or enhance their brands.
- Is sustainability an opportunity or cost? There was a general agreement that there is no choice but to treat it as an opportunity.

In the NIST Sustainable Manufacturing Workshop we found evidence that the more experienced manufacturing firms see opportunities in sustainability beyond mere compliance with regulations – in fact, they view this as a driver of innovation. They find that by adopting lean manufacturing practices they can reduce waste (a sustainability goal) while saving associated costs. They also see new market opportunities if they can introduce innovative materials, processes, and products to meet the global economic, societal, and environmental sustainability needs.

In the meantime, several non-governmental and standards development organizations are actively engaged in proposing and issuing guidelines, standards, and regulations. It was clear at the NIST workshop that they need some urgent coordination. Several academics have studied these problems and are trying to bring some order and understanding to various sustainability practices. It is encouraging to see that the academic community that studies these problems includes economists, who are proposing methods to monetize many of the sustainability metrics.

Based on the NIST Sustainable Manufacturing Workshop, the major challenges faced by the U.S. manufacturing industry in their pursuit of sustainability goals can be summarized as: (1) they are unable to accurately measure economic, societal, and environmental impacts and costs of their products during the entire life cycle and across their supply chain; (2) full life cycle analysis (LCA) of products requires new methods to analyze, integrate, and aggregate information across hierarchical levels, organizational entities, and supply chain participants; and (3) they lack neutral and trusted programs to demonstrate, deploy, and accredit new sustainable manufacturing practices, guidelines and methods.