

Rapid Small Lot Manufacturing*

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ABSTRACT

The direct connection of information, captured in forms such as CAD databases, to the factory floor is enabling a revolution in manufacturing. Rapid response to very dynamic market conditions is becoming the norm rather than the exception. In order to provide economical rapid fabrication of small numbers of variable products, we must design with manufacturing constraints in mind. In addition, flexible manufacturing systems must be programmed automatically to reduce the time for product change over in the factory and eliminate human errors. Sensor-based machine control is needed to adapt idealized, model-based machine programs to uncontrolled variables such as the condition of raw materials and fabrication tolerances.

KEYWORDS: sensors, control, CAD, manufacturing, information

INTRODUCTION

Sandia National Laboratories is responsible for the design and fabrication of a wide range of electromechanical products for national defense. For decades, Sandia's mission was accomplished by designing, developing, producing, and deploying new weapon systems to replace systems already in the inventory. However, the climate in which this mission must be fulfilled has changed dramatically. The inventory, which was once being continuously renewed through the introduction of new systems and the retirement of older designs, now consists of reduced numbers which will not be replaced in the foreseeable future. One consequence of this situation is that the production rates for defense related products has decreased dramatically and manufacturing must be far more agile and responsive than in the past [1].

A key issue in defense manufacturing today is affordability of highly specialized products in small lot quantities. In response to the demand for more cost effective approaches, the Intelligent Systems and Robotics Center (ISRC) at Sandia is developing technology to reduce both the time and cost for producing defense products. A key strategy for providing cost effective small lot manufacturing is the elimination of production defects early in

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manufacturing. Traditionally, defect introduction is high at the onset of production as new processes are placed into production and as production personnel adjust operational parameters to produce product. Technologies for defect free initiation of production are being developed to eliminate such "start up issues."

Sandia's basic strategy is to treat the entire product life cycle as a system. This strategy stimulates the development of systems engineering technologies and tools for coupling traditionally separate disciplines such as design, fabrication, and deployment. This paper reviews Sandia's evolving program and discusses key research advancements underway to achieve low cost, on-demand manufacturing of small quantities of highly customized products.

Sandia's basic approach is to develop technologies that enable information to be delivered directly to the machines which fabricate products. Much effort and benefit has been derived from connecting information to people over the Internet. The next step of connecting information to machines will dramatically impact the way products are designed and fabricated.

DISTRIBUTED INFORMATION SYSTEMS

Sandia must realize product in a geographically disperse environment in which the needed resources such as software analysis tools, design data, test facilities, requirements databases, and people are rarely collocated. Yet, effective design and production requires that these resources and more be brought to the desktops of engineers addressing real product design and fabrication issues. As a result of this need for widespread communication of information, Sandia has developed an object oriented communication environment termed the Product Realization Environment (PRE). PRE was conceived with the realization that much of the information needed during design and production resides in heterogeneous environments. Thus, information resident within a commercial CAD database in New Mexico may have to be communicated quickly to the desktop of an analyst in California. It is unrealistic to redo all existing software in a common format so PRE employs a Common Object Request Broker Architecture (CORBA) compliant environment. In this environment, interface software (termed wrappers) converts heterogeneous software formats into a standard format for communication to a distant application. Upon arriving at the destination, another CORBA wrapper translates the received information to make it available to the application requesting the information. The object oriented architecture of PRE is shown in Figure 1. Due to the CORBA interfacing standards, application engineers need not bother with specific interface coding tasks. They simply request the information and it is delivered to them for their use transparently as long as the appropriate information is supplied and requested. PRE-based communication is propagating widely within Sandia and is allowing the creation of virtual design and production teams.

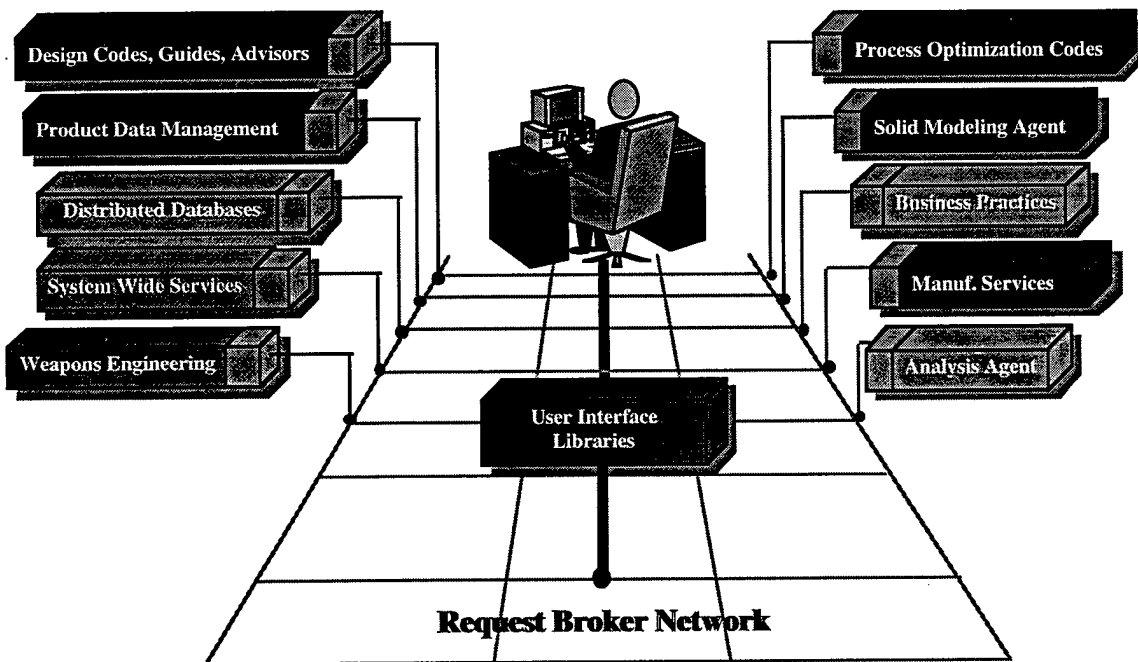


Figure 1. Object oriented architectures bring needed information to the engineer's desktop.

An important issue in a distributed design and production environment is the delivery of expertise as well as information. Expertise in the form of human creativity and understanding is key to reducing the time and cost of making product in a rapidly changing environment. Another paper in this session [2] addresses the creation of collaborative environments in situations where both information and people are geographically dispersed. A key role of PRE and the software tools it supports is then to link the best minds together to quickly solve problems. Software analyses and simulations serve as tools to enhance human problem solving. This is accomplished in two ways. Software analyses quickly provide the "80% solution" and allow human experts to spend their time working on the truly difficult issues to more quickly achieve the needed "100% solution." In addition, interactive simulations communicate the results of analyses and design modifications instantly to a dispersed team of experts much as if they were in the same room. "I see what you mean" replaces "I'll get back to you on that after I get your results."

INTEGRATED PRODUCT AND PROCESS MODELING

Modeling and simulation tools allow experts to achieve solutions quickly and to communicate those results to other members of a design and production team. There are several key attributes which derive from integrating the modeling and simulation of the product performance and manufacturing. While product design traditionally consumes a small but significant portion of the overall cost of realizing product, it locks in the major portion of the product's cost because a product's design determines how it will be manufactured. Sandia has initiated a major effort to develop the tools to allow the assessment of manufacturing impacts during product design. An example is the assessment of assembly processes during the design of complex products. It is not uncommon for a particularly complex system or subsystem to encounter problems during final assembly due to designers overlooking geometric inconsistencies. The ISRC has developed an assembly analysis tool entitled Archimedes [3] which can use the geometric information captured in a CAD database to assess a particular design for ease of assembly. Archimedes uses only geometry information to determine possible assembly sequences for complex assemblies. The allowable assembly sequences and motions can be constrained based upon knowledge of which subassemblies may be provided by suppliers, machine and human dexterity capabilities available in the factory, and preferred batching sequences during fabrication. As a result, a designer can fully understand the consequence of design decisions on manufacturing very early on. An example of a product automatically analyzed by Archimedes for ease of assembly is shown in Figure 2. The assembly sequence can be animated and made available as an MPEG to allow geographically distributed team members to review the assembly sequence and apply constraints to fully evaluate a design before any actual hardware is fabricated. Other manufacturing analysis tools under development at Sandia include Smartweld, a welding advisor, Holdfast, a fixture design advisor, machining advisors, forging advisors, and others [4,5]. A key role of all of these software tools is to evaluate manufacturing impacts very early in the design cycle where changes can be made easily and quickly prior to commitment of fabrication resources.

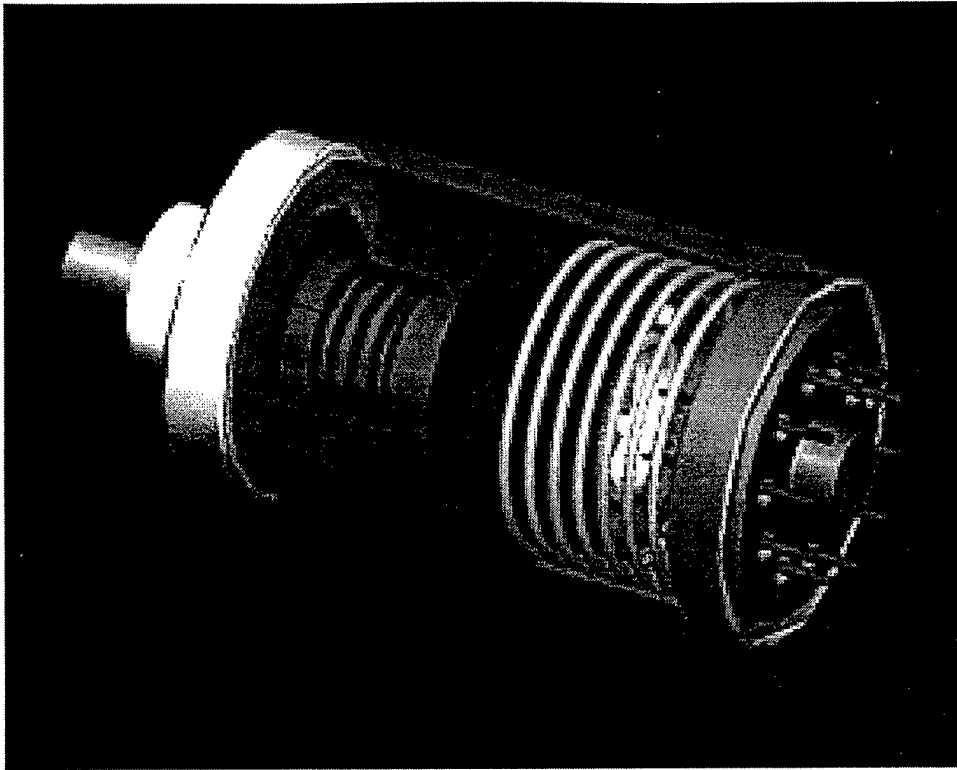


Figure 2. Geometric reasoning allows automated planning of assembly operations for complex devices such as this accelerometer.

DIRECT COMPILATION OF PROCESS CONTROL CODE

Many of the same models used during evaluation of product design for ease of manufacturing can be used to sequence and program actual fabrication equipment. For example, the Archimedes automated assembly planner discussed above can be used to directly program assembly machines used during production. Thus, the assembly sequences and motions defined by Archimedes can be communicated to the factory floor using an environment such as PRE. The motions through space which describe required assembly motions can be coupled to the kinematics of assembly machines and robots to directly compile the machine programs needed to carry out the assembly operations. Figure 3 shows the Agile Manufacturing Prototyping System (AMPS) at Sandia used to perform CAD-based rapid physical prototyping of electromechanical products. AMPS is used to physically validate automated process scripting and scheduling as well as CAD-based programming techniques. Tools such as Archimedes are often coupled with visualization tools to program simulations of factory equipment so that the designers can fully understand the impact of design decisions. The same code which drives the simulation can drive the actual fabrication equipment if the simulation is an accurate representation of the actual factory environment. Thus, the use

of modeling and simulation to evaluate the impact of design decisions on fabrication serves two purposes. One purpose is the evaluation of the design. The second purpose is the generation of the actual control code for the fabrication process. Direct programming of fabrication machines from CAD-based information eliminates programming errors while greatly reducing the time required to translate design information into fabrication information. This allows very rapid response to product line changes as well as reuse of expensive capital equipment to maximize factory utilization.

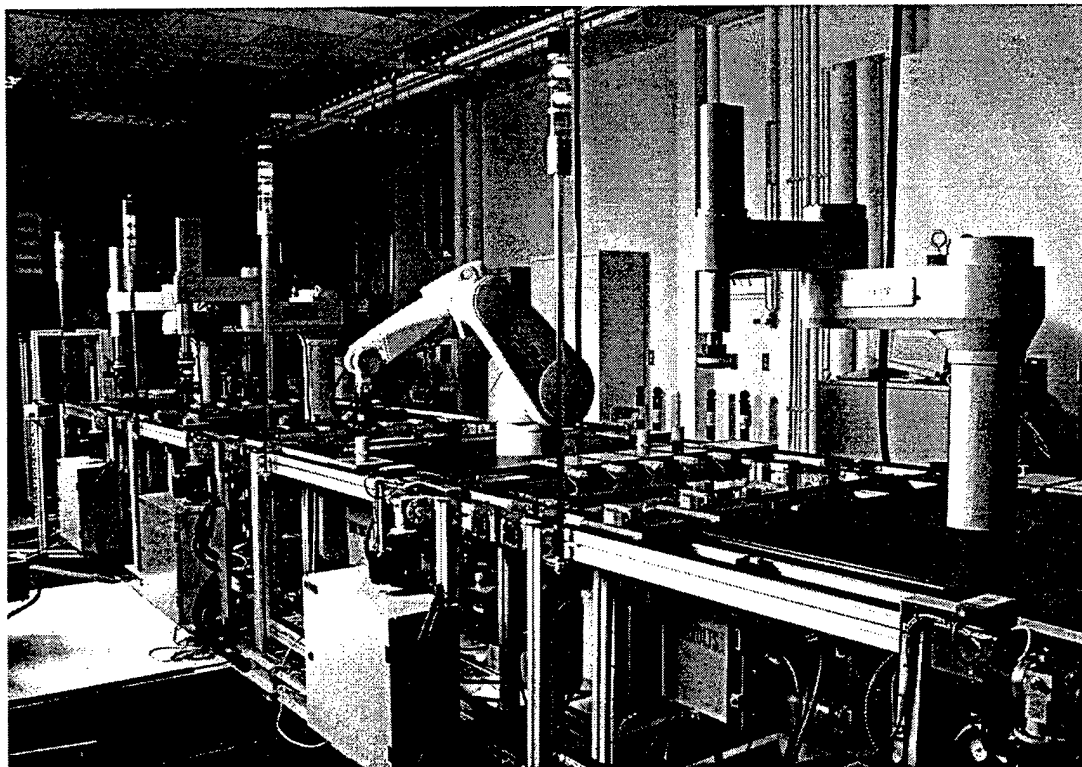


Figure 3. AMPS uses information and object oriented software architectures to allow rapid rescripting and reprogramming of assembly operations.

MODEL- AND SENSOR-BASED CONTROL

In order to automatically program machines for production from the information contained in CAD databases, the machines must be able to compensate for differences between actual conditions and the ideal conditions represented in the CAD models. Such differences are inherent in the nature of CAD representations since, at the very least, all dimensions are provided with tolerances. In addition, the starting condition of many of the raw materials used in manufacturing are not well known. Finally, the nature of many manufactured products are such that it is very difficult to hold precise tolerances. For example, the array of tubes shown in Figure 4 is part of a

rocket engine nozzle manufactured by Rocketdyne. These tubes must be brazed together and there must be no air gaps since good heat transfer between tubes is critical to proper functioning of the engine. Past practice had called for a technician to manually apply braze past and then the entire engine assembly would be placed in a furnace to melt the paste and thus braze the tubes together. Due to the difficulty of achieving a uniform application of the braze paste using manual application methods, product reject rates were high, there was significant waste of expensive and hazardous braze paste, and the entire process was very slow. Sensor-based control however, greatly increased production rates and quality. The sensor shown in Figure 4 is a capacitive sensor which senses the location of adjacent tubes of the nozzle and sends information to the controller of the robot to precisely position the braze paste dispenser unit so that exactly the right amount of braze paste is applied in exactly the right place [6]. Thus the capacitive sensor adjusts the nominal model-based trajectory of the robot to compensate for lack of precision information about the workpiece. Sensor-based control when coupled with model-based information can thus provide the agility to deal with product variability. This increases productivity while increasing quality.

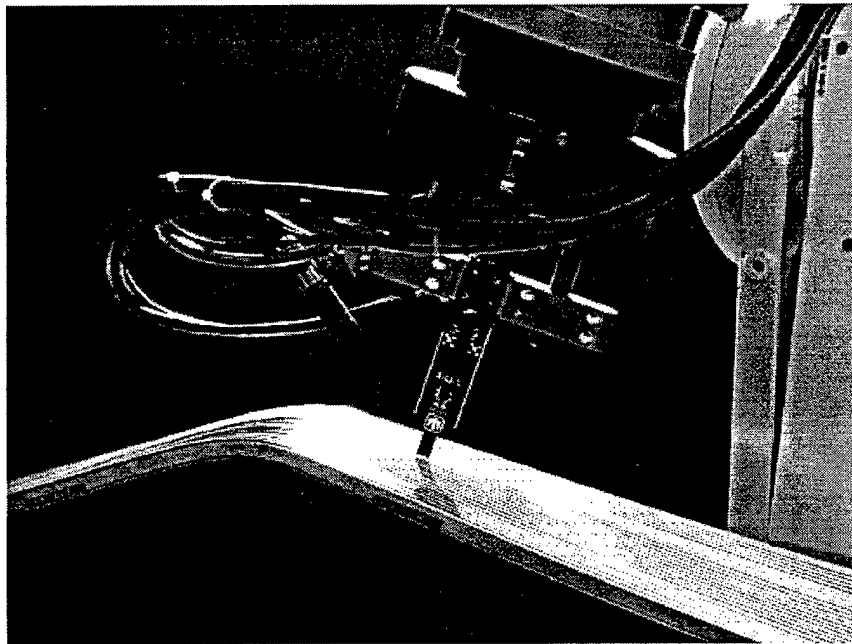


Figure 4 Sensor-based control adapts robot motions to physical environment during precision braze paste dispensing.

CONCLUSION

Technologies which reason about and deliver information directly to both design teams and to fabrication facilities can enable the cost effective

manufacturing of small product lots. A key technology to enable such information driven manufacturing are sensor-based control technologies which can adapt nominal information to the specifics of actual manufacturing conditions. Such agility allows rapid response to changing markets. The direct fabrication of products designed with manufacturing constraints in mind will become common place as the technologies mature and the cost of high speed computing continues to fall.

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