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EMERGING TECHNOLOGIES IN MANUFACTURING ENGINEERING

Prepared by:
The Management and Staff of the
Center for Manufacturing Engineering

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards
and Technology
National Engineering Laboratory
Center for Manufacturing Engineering
Gaithersburg, MD 20899

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FOREWORD

This is an internal report produced by the managers and staff of the Center for Manufacturing Engineering for planning purposes only. It represents our current best thinking about emerging technologies in manufacturing engineering, the impact these technologies will have on our programs, and the directions our programs will go if sufficient resources are available. The emerging technologies discussed are those that we believe will require increased support and leadership from CME in coming years. Not all aspects of each plan presented have been approved, but some work is already underway in each area. Each emerging technology is linked directly to those listed in a forthcoming Department of Commerce report, referenced later in this document. For convenience, the emerging technologies discussed in this report are summarized below.

Advanced Manufacturing Technology

The core of the CME effort in advanced manufacturing is the Automated Manufacturing Research Facility (AMRF). The AMRF has played a significant role in the identification and development of emerging technologies in manufacturing, and indeed has been a catalyst in the legislative process that resulted in the Technology Competitiveness Act. The AMRF is a unique engineering laboratory. The facility provides a basic array of manufacturing equipment and systems – a "test bed" – that researchers from NIST, industrial firms, universities, and other government agencies can use to experiment with new standards and to study new methods of measurement and quality control for automated factories.

NIST, as the nation's primary laboratory for measurement science and engineering, has two principal goals for its automated manufacturing program: to supply American industry with a radically new way of making precisely machined parts – with dimensions that can be referenced to national measurement standards maintained by NIST – and to encourage the modernization of American manufacturing by providing the technical information necessary to develop standardized "interfaces" between various types of equipment. NIST also is using this facility as a test bed for research on the next generation of "knowledge-based" manufacturing systems – automation systems that incorporate artificial intelligence capabilities.

Small-Scale Advanced Manufacturing

Small job shops – operations with fewer than 50 employees – make up about 85 percent of U.S. metal fabrication facilities and account for about 75 percent of all U.S. metal fabrication. They are running substantially behind their overseas competitors in the use of modern technology. In Japan, for example, approximately 30 percent of all machine tools are computer-controlled; in the United States, fewer than 11 percent. Sweden and West Germany also have more computer-controlled equipment than the United States.

What modern technologies are commercially available, affordable, and useful to the small job shop? How are they best introduced? What return on investment might be expected? To help answer these questions, NIST is using its own job shop to conduct an experiment in the practical implementation of computer-integrated manufacturing.

PDES and Product Data-Driven Engineering

The weak link in the chain from customers' needs to marketable products would seem to be toward the production end; but in fact it is right at the beginning, in our design practice. U.S. design is often inefficient, detached from the production process, undocumented in terms of the rationale for design decisions, and production-facility dependent.

However, there exists a method that has been demonstrated to improve the design process. Documented use of the method has produced a reduction of 50% in the number of engineering design changes, a reduction of 40-60% in the total product development time, a reduction of 30-40% in the manufacturing costs, and a reduction of 75% in the scrap and rework of manufactured products. The method is called "product data-driven engineering" or "concurrent engineering." It is a systematic approach to the integrated, concurrent design of products and their related processes and materials, including manufacture and support.

A critical component of the development of a PDES environment is the ability to define and test specific PDES applications and implementations. The National PDES Test Bed, already under construction at NIST, will be expanded to address the bigger issue of applications of intelligent machines and processes. The test bed will become a model for future test beds that will be established throughout the world. The test bed will also serve as a model for software and hardware configurations and personnel resources needed to test and implement PDES.

Intelligent Machines

The objective of the proposed NIST program will be to develop performance criteria, measurement methods, and standards for intelligent machines that will speed the development and use of this technology and facilitate transactions between buyers and vendors in the marketplace.

An intelligent machine or process can be thought of as a plant which operates on materials and parts. This plant may be a robot, an automatic factory, a materials processing plant, or bioengineering facility. Products produced may be discrete mechanical or electronic parts, or materials in solid, liquid, or gaseous form. An intelligent machine may also be a vehicle that accomplishes some task of transportation, exploration, or weapons delivery. Intelligent vehicle systems use object and terrain databases to generate process plans and control programs.

The proposed NIST program will develop the theory and technology base necessary to establish standards for, and measure the performance of, future generations of intelligent machines and processes.

Nanotechnology

Industry experts, worldwide, agree that present miniaturization processes and devices will run up against fundamental limits by the early 1990's; limits that will require new species of devices and new manufacturing processes. The road to the ultimate miniaturization will, therefore, be a combination of materials processes, devices and systems which are evolutions of current approaches and revolutionary processes based on molecular designing and engineering, revolutionary quantum well and box devices, and radical new computer architectures such as neural networks and cellular automata. To keep up with the rapid worldwide evolutionary pace and to provide support for revolutionary developments, U.S. industry will have to become much more sophisticated in all aspects of nanotechnology and all its associated enabling technologies that are being developed to cope with the special problems resulting from the extreme reductions in device size.

The proposed program will enable NIST, working collaboratively with U.S. industry and other governmental and university laboratories, to develop a generic science-and-technology base for nanotechnology. Because of the extreme dimensional precision and accuracies demanded by nanotechnology, NIST will develop and make available to domestic industries appropriate instrumentation for generating and measuring nanometer displacements, highly accurate nanometer length artifacts, and important data on materials and processes. With this strong base in manufacturing and measurement and a long standing expertise in intelligent machines, NIST will also contribute to the development of new devices and circuit architectures.

Table of Contents

INTRODUCTION

When the Technology Competitiveness Act, a subsection of the Omnibus Trade and Competitiveness Act, was signed into law on August 23, 1988, it changed the name of The National Bureau of Standards and added to our mission several new and expanded functions which build on the technical expertise of NBS. The new name is the National Institute of Standards and Technology (NIST) and the new functions provide an increased emphasis on supporting industry to improve competitiveness by enhancing the rapid commercialization of technology. The essence of the new mission is given in the following functional statement excerpted from the act

> "...to assist industry in the development of technology and procedures needed to improve quality, to modernize manufacturing processes, to ensure product reliability, manufacturability, functionality, and cost-effectiveness, and to facilitate the more rapid commercialization, especially by small- and medium-sized companies throughout the United States, of products based on new scientific discoveries in fields such as automation...."

Focusing on the needs of U.S. industry is nothing new to NIST: from its establishment in 1901, it has remained the only federal agency with a specific mission to support U.S. industry. We have concentrated during that time on providing the measurements, calibrations, and quality assurance techniques that are an important part of commerce and technological progress. In fact, these functions are reaffirmed in the act:

> "...to develop, maintain, and retain custody of the national standards of measurement, and provide the means and methods for making measurements consistent with those standards..."

> "...to assist industry in the development of measurements, measurement methods, and basic measurement technology..."

> "to assure the compatibility of United States national measurement standards with those of other nations...."

Thus the Omnibus Trade Bill requires that NIST expand its efforts to transfer technology that can improve productivity of American industry, while maintaining its reputation as the one of the nation's finest measurement and general purpose scientific and engineering laboratories. This new emphasis on supporting industry to improve productivity and competitiveness and the explicit assignment that it be accomplished in broad areas of technology is a significant event. It is clearly a result of the growing national debate which has focused on the decline of U.S. industry's competitiveness and resultant loss of market share in the global marketplace.

This rapid loss of competitiveness of American industry in international markets is an extremely serious problem with wide-ranging consequences for the United States' material well-being, political influence, and security. The national debate on this subject has identified many possible culprits, ranging from budget deficits to short-term, bottom-line thinking on the part of U.S.

management. Nevertheless, among them certainly are the slow rate at which new technology is incorporated in commercial products and processes, and the lack of attention paid to manufacturing. There is a clear need to compete in world markets with high-value-added products, incorporating the latest innovations, manufactured in short runs with flexible manufacturing methods. Research, management, and manufacturing methods that support change and innovation are key ingredients needed to enhance our nation's competitive position.

As a nation, we have been slow to capitalize on new technology developed from America's own intellectual capability. Many ideas originating in the American scientific and technical community are being commercially exploited in other parts of the world. In the past, small and mid-sized companies have led U.S. industry in innovation. Our government must now find ways to help such companies meet the demands of global competition, when the speed with which firms are able to translate innovations into quality commercial products and processes is of utmost importance.

This report describes some efforts underway at NIST to aid U.S. manufacturers in their own efforts to compete in the global marketplace. At the center of these efforts are the programs of the Center for Manufacturing Engineering. Thus, the report focuses on these programs and projects.

In order to put these programs in focus, we provide in the next section a brief discussion of the mission and objectives of the Center. After that section, Section 3 provides information on advanced manufacturing as an emerging technology, including details on the Automated Manufacturing Research Facility, its goals and objectives, and some of its outputs. Section 4 is a discussion of the new emerging technology of PC-based, small-scale advanced manufacturing specifically suited to the small- and medium-sized manufacturing firms in the U.S. Section 5 describes the emerging technology of product data-driven engineering, its relationship to concurrent engineering, and our efforts to support the development of the emerging international standard known as Product Data Exchange Specification. Section 6 describes our program in intelligent machines and its effects across both the defense and the private sectors, and Section 7 is a discussion of the exciting new technology of the very, very small: nanotechnology.

THE CENTER FOR MANUFACTURING ENGINEERING

The Center for Manufacturing Engineerin (CME) is one of five Centers making up the National Engineering Laboratory of NIST. Center staff maintain competence in, and develop, technical data, findings, and standards in manufacturing engineering, precision engineering, mechanical metrology, mechanical engineering, automation and control technology, industrial engineering, and robotics to support the discrete parts manufacturing industries. The Center develops measurement methods particularly suited to the automated manufacturing environment as well as traditional mechanical measurement services. The Center also develops the technical basis for interface standards between the various components of fully automated discrete part manufacturing systems. The Center consists of a staff of approximately 300, with an annual budget of approximately $25 million, both of which are devoted to the program goal, "to contribute to the technology base which supports innovation and productivity enhancement in the discrete parts manufacturing industries on which the Nation's economic health depends."

The Center is managed by the Director, the Deputy Director, the Administrative Officer, the Program Manager of the Automated Manufacturing Research Facility, and the Chiefs of the five Divisions: the Precision Engineering Division, the Automated Production Technology Division, the Factory Automation Systems Division, the Fabrication Technology Division, and the Robot Systems Division. Each of these Division's programs, including samples of the outputs of these programs, are discussed in more detail below. Following those discussions, we provide descriptions of the major facilities in the Center.

The Precision Engineering Division

This five-group division develops and conveys metrological principles and practices to support precision-engineered systems vital to U.S. manufacturing industries. Its general work encompasses the physics and engineering of systems which generate, measure and control to high resolution the length-dimensional quantities of position, distance, displacement and extension. Specific work focusses on: electron-, optical- and mechanical-probe microscopies; coordinate measuring machines; and metrology-intensive production systems for automated manufacturing, precision metal-working and integrated-circuit fabrication. Of special concern are industries dealing with the fabrication of nanometer-scale structures such as micro-machined mechanical components and lithographically produced electronic devices – an emerging technology certain to be of major commercial significance, fierce international competition, and requiring broad advances in metrology for its support.

Sample outputs include:

- Development of microprocessor-based sensor systems for machine tools
- Calibration and Measurement Assurance Programs for gage blocks and other dimensional standards including standards for the microcircuit program

- Calibration and Map Programs for Mass Standards
- Error correction algorithms for measuring machines and machine tools
- Demonstration of robot-tended inspection machines
- Demonstration of optical measurement of surface finish
- Standards for integrated circuits
- Ultra-high precision measuring machines
- Standard Reference materials for photomask calibration

The Robot Systems Division

The Robot Systems Division is composed of five Groups: the Intelligent Control Group, the Sensory Intelligence Group, the Systems Integration Group, the Unmanned Systems Group, and the Performance Measures Group. The goal of the Robot Systems Division is to develop the technology base necessary to characterize and measure the performance of, and establish standards for, future generations of intelligent machines systems. To do so will require the extension and fusion of the concepts of artificial intelligence and the techniques of modern control to make control systems intelligent and make artificial intelligence systems operate in real-time.

The control system architecture developed for the Automated Manufacturing Research Facility (AMRF) at the National Institute of Standards and Technology had its foundations in robotics research. The concepts of hierarchical control, task decomposition, world modeling, sensory processing, state evaluation, and real-time sensory-interactive, goal-directed behavior are all a part of this control architecture. These concepts are derived from the neurosciences, computer science, and control system engineering. The result of the AMRF project is a generic modular intelligent control system with well defined interfaces. This control architecture provides a first generation bridge between the high level planning and reasoning concepts of artificial intelligence and the low level sensing and control methods of servo mechanisms.

Industrial robots and computer controlled machine tools for manufacturing are only the first of many potential applications of robotics. Future applications will be in less structured, more unpredictable, and often more hostile environments. The application of robotics and artificial intelligence to other sectors of industry, commerce, space, and defense has the potential to vastly increase productivity, improve quality, and reduce the cost of many different kinds of goods and services.

The Robot Systems Division expects that the robotics technology currently available or being developed (mostly with NASA and Department of Defense funding) will be applied to produce a wide variety of intelligent machine systems. The Division proposes to position itself to meet the measurement and standards needs of this emerging industry by being actively involved in a variety of developments so that it understands the underlying technology and discerns the measurement and standards requirements.

The Robot Systems Division is currently working on applications of the AMRF control system architecture to space telerobots for satellite servicing, to coal mine automation, shipbuilding, construction, large scale (high payload, long reach) robots, multiple cooperating semi-autonomous land vehicles (teleoperated and supervised autonomy), and nuclear submarine operational automation systems.

Sample outputs include:

- Reference model architectures, performance measures, interface guidelines, and standards for intelligent, real-time control systems
- Advanced concepts in robot vision, sensory processing, world modeling, and intelligent real-time control systems.

The Robot Systems Division has developed a Department of Commerce long-range initiative for fiscal years 1990-1994 to:

- Conduct basic research in the fundamental science of intelligent machine systems and perform experiments in machine vision, sensory fusion, knowledge representation, decision theory, intelligent controls, mechanical systems, adaptive and learning systems, design databases, and software engineering.
- Develop a formal theory of intelligent machines and a set of methods for measuring levels of intelligence. These include both theoretical (mathematical, logical) and empirical (performance) measures.
- Build a facility for conducting experiments and evaluating the performance of intelligent machine systems for manufacturing and construction applications. This facility will include computer systems for sensors and measuring devices, mobile robots, control systems, and software development and testing environments. The facility will be used to develop and test open systems architectures, define performance measures, and evaluate proposed standards.

This initiative was approved by the NIST Executive Board and recommended to DOC for funding at the $5M per year level. It was approved by DOC for $2.5M in FY91.

The Factory Automation Systems Division

To remain competitive in world markets, the United States must continually improve its manufacturing strength. Current manufacturing methods must be refined and new technologies must be created to develop new products, reduce production costs, shorten commercialization lead times, and raise overall product quality. In recent years, information technology and information systems have become increasingly important in the manufacturing enterprise. The primary goal of the Factory Automation Systems Division is to provide a focus for national research and standards efforts relating to information systems for manufacturing.

This Division is composed of five Groups: the Production Management Systems Group, the Integrated Systems Group, the Machine Intelligence Group, the PDES Test Bed Group, and the Manufacturing Systems Standards Group. The Factory Automation Systems Division carries out its mission through the application of an engineering paradigm that results in a leading role in national and international standards committees relating to information technology and manufacturing systems for scientists and engineers in the Division. The paradigm involves the implementation of a research "testbed" that demonstrates new information technologies and engineering systems for the manufacturing enterprise. The experience of testing new technologies is used by

Division staff to develop and promote manufacturing interface standards and product data exchange standards in automating manufacturing systems.

The Division staff perform research in the information technology requirements for such manufacturing processes as product design, process planning, equipment control (e.g. machine tools, measurement machines), and logistics support (e.g. maintenance & repair). This research leads to an understanding of integrated database requirements to support product life-cycles, requirements that can be reflected in both standards for product data exchange and information technology frameworks needed to manage the data.

The Division staff perform research in such information technologies as information modeling, data dictionaries, distributed database systems, product knowledge representations, and communication networks. The Division staff perform research in such engineering technologies as design theory, geometric modeling, process and factory engineering modeling, product-feature driven manufacturing processes, and factory control.

In addition, the Division staff perform research into the testing methodologies required for measuring the ability of engineering systems to perform in conformance with the product and process interface standards that are being implemented.

Sample outputs include:

- Interface guidelines and standards for large distributed real-time control systems
- Development of design tools for automated manufacturing systems
- Development of factory communications network
- Development of advanced intelligent factory control systems
- Development of a CAD-directed inspection system
- Development of a distributed data system for an automated factory
- Development of an automated process planning system for manufacturing
- Architecture specifications for distributed, heterogeneous, factory database management systems
- Architecture for the representation of geometric models of machined parts for use by manufacturing engineering systems

The Automated Production Technology Division

The Automated Production Technology Division is also composed of five Groups: the Ultrasonic Standards Group, the Acoustic Measurements Group, the Sensor Systems Group, the Sensor Integrations Group, and the Force Group. The Division develops and maintains competence in the integration of machine tools and robots up to and including the manufacturing cell level. The Division develops and maintains computer-assisted techniques for the generation of computer codes necessary for the integration of machine tools and robots. The Division also develops the interfaces and networks necessary to combine robots and machine tools into workstations and workstations into manufacturing cells. In addition, the Division performs the research and integration tests necessary for in-process monitoring and gaging. The Staff maintains competence in engineering measurements and sensors for static and dynamic force-related quantities and other parameters required by the discrete parts industry. They also conduct fundamental research on the nature of the measurement process and sensory interaction, as well as the development, characterization, and calibration of transducers used in discrete parts manufacturing.

Sample outputs include:

- Sensors for automated manufacturing of batched parts
- Sensors for in-process measurements
- Application of research for automated manufacturing cells
- Proposed interface standards for sensors for machine tools
- Physical standards for ultrasonic flaw detection
- Calibration of force to 1 million lbs. deadweight
- Calibrations of vibration and acoustic sensors

The Fabrication Technology Division

This Division has three Groups: the Support Activities Group, the Special Shops Group, and the Main Shops Group. The Fabrication Technology Division designs, fabricates, repairs, and modifies precision apparatus, instrumentation, components thereof, and specimens necessary to the experimental research and development work of NIST. Services include: engineering design, scientific instrument fabrication, numerically controlled machining, welding, sheet metal fabrication, micro fabrication, grinding, optical fabrication, glassblowing, precision digital measuring, tool crib, and metals storeroom. The Division also develops and maintains competence in CAD/CAM, automated process planning, and shop management systems.

Sample outputs include:

- Fabrication of pump inducer for cryogenic fluids
- Fabrication of diamond anvil high pressure-high temperature cells
- Fabrication of adjustable radius curved crystal mount
- Fabrication of high accuracy manometers
- Fabrication of dilatometer
- Fabrication of beam line for 10 meter X-ray camera

The Automated Manufacturing Research Facility

This facility is a research laboratory for study of the measurement and standards problems of the "factory of the future." It consists of 5,000 sq. ft. of high bay shop area, occupied by three machining workstations, a cleaning and deburring workstation, an inspection workstation, and an automated material handling system. An extensive network of computers makes up the real-time control, distributed data administration, and manufacturing engineering elements of the facility. Research is currently supported on sensors, real-time control, deterministic metrology, production management and scheduling, data administration, communications, and preparation of manufacturing data.

The Metrology Electron Microscope System

This facility, used to calibrate micro-length reference artifacts, consists of a commercial, research quality scanning electron microscope which has been modified to include a scanning specimen stage whose displacement is measured by an interferometer with a stabilized helium-neon laser light source. A measurement consists of scanning the object across the fixed electron beam, which acts as a fine "cross-hair," while logging one or more of the various electron output signals versus the stage displacement on a minicomputer-based data acquisition system.

The Standard Force Generators

This facility consists of six deadweight machines that can provide vertical forces ranging from 44 newtons (10 pound force) to 4.4 million newtons (1 million pound force). The applied forces, known to better than 20 parts per million, enable accurate calibration of load cells and other force sensors, as well as related research.

The Acoustical Anechoic Chamber

This facility provides a free-field environment for research and calibrations on measurement of the directivity of sound sources and the directional response of microphones and sensor arrays. The 450-m^3 free volume of the chamber is lined with fibrous glass wedges that absorb 99 percent or more of the normally incident sound energy over a frequency range from 40 Hz to over 60,000 Hz.

The Shop of the '90s

This facility is setup to study the problems encountered by private sector job shops when upgrading and automating. Included in this study are personal computer based cost-estimating, process planning, tool room management, CAD/CAM, and inspection.

* * *

With this discussion of the mission, structure, and objectives of the Center for Manufacturing Engineering as a foundation, we can now proceed with a discussion of the emerging technologies in manufacturing engineering in the context of the this mission. The programs and projects described in the following sections exist and are in place and operating, albeit at a much reduced level of effort from that which we feel is necessary to fulfill our mission to support the U.S. discrete parts manufacturing industry. CME has been seeking additional federal budget appropriations for these programs for some time, and will continue to do so. Nevertheless, each section describes an emerging technology in manufacturing engineering that we see as requiring increased support and leadership from CME in the coming years. Each ties in directly to the relevant portions of the list of emerging technologies given in a forthecomeing Department of Commerce Report on the subject.[1] For convenience, these portions are reproduced here as Tables 1-2.

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1 Emerging Technologies: a survey of technologies and economic opportunities, forthcoming Department of Commerce Report.

TABLE 1
FLEXIBLE COMPUTER-INTEGRATED MANUFACTURING

Major Technology Elements:

CAD, CAE, CALS, CAM, CIM, FMS, PDES, Control Architectures, Adaptive Process Control.

What It Is:

A new approach to manufacturing and construction requiring not only technology but management and engineering adjustments. Use of computers, robots, and intelligent machines in the total manufacturing and construction enterprise. Integration of both the materials handling and processing systems as well as the planning, logistics, and business systems.

Underlying Science:

Control theory; operations research; electrical, mechanical, manufacturing, and industrial engineering; business and management science.

Engineering Barriers:

Need for data structures to describe product and process. Concurrent engineering to integrate design and manufacture. More reliable machines, automated process planning, "smarter" robots, more accurate and inexpensive sensors.

What Is New or Better:

Reduce cost and time to manufacture, improve quality; permit competition by scope and variety of product line; reduce inventory, manufacture to order rather than to plan.

Impact on What Products or Processes:

Manufacturing discrete and batch parts; economical small lot manufacture; continuous and adaptive processes; chemicals, pharmaceuticals, steel, paper, textiles; residential and commercial construction, public works.

Likely Markets and Industries:

High-tech manufacturing, automotive, construction, home appliance, computers, office machines, machine tools, aerospace.

DOD Critical Technologies Overlap:

5. Machine Intelligence/Robotics

Annual Sales by Year 2000:

U.S.: $10-20B

World: $20-40B

TABLE 2
ARTIFICIAL INTELLIGENCE

Major Technology Elements:

Intelligent Machines, Intelligent Processing of Materials and Chemicals, Expert Systems.

What It Is:

Electronic and electromechanical systems incorporating knowledge-based control systems.

Underlying Science:

Data structures, data management systems, software engineering, servo engineering, biological and cognitive sciences and engineering, numerical analysis, statistical physics.

Engineering Barriers:

Size of databases, computational speed, lack of formal tools for knowledge representation.

What Is New or Better:

Improved performance over current systems which are at most capable of a limited number of responses to events fully anticipated in advance. Improved graphical representation of results.

Impact on What Products or Processes:

Manufacturing of machine tools, robots, construction equipment. Materials and chemical processing; computer-aided design; signal and image processing. Analysis of medical tests or symptoms.

Likely Markets and Industries:

Manufacturing, mining, security, health care, construction, materials processing, communication and financial services.

DOD Critical Technologies Overlap:

5. Machine Intelligence/Robotics
9. Sensitive Radars
11. Automatic Target Recognition
13. Data Fusion

Annual Sales by Year 2000:

U.S.: $5B

World: $12B

Objective

The core of the CME effort in advanced manufacturing is the the Automated Manufacturing Research Facility (AMRF). The AMRF has played a significant role in the identification and development of emerging technologies in manufacturing, and indeed has been a catalyst in the legislative process that resulted in the Technology Competitiveness Act. The AMRF is a unique engineering laboratory. The facility provides a basic array of manufacturing equipment and systems—a "test bed"—that researchers from NIST, industrial firms, universities, and other government agencies can use to experiment with new standards and to study new methods of measurement and quality control for automated factories.

The AMRF includes several types of modern automated machine tools, such as numerically controlled milling machines and lathes, automated materials-handling equipment (to move parts, tools, and raw materials from one "workstation" to another), and a variety of industrial robots to tend the machine tools. The entire facility operates under computer control using an advanced control approach pioneered at NIST. The AMRF incorporates some of the most advanced, most flexible automated manufacturing techniques in the world.

NIST, as the nation's primary laboratory for measurement science and engineering, has two principal goals for its automated manufacturing program: to supply American industry with a radically new way of making precisely machined parts—with dimensions that can be referenced to national measurement standards maintained by NIST—and to encourage the modernization of American manufacturing by providing the technical information necessary to develop standardized "interfaces" between various types of equipment. NIST also is using this facility as a test bed for research on the next generation of "knowledge-based" manufacturing systems—automation systems that incorporate artificial intelligence capabilities.

Background

Historically, manufacture and measurement have always been two separate processes. A machinist would cut a part on a milling machine and stop periodically to check dimensions with calipers and gages. As manufacturing techniques became more and more efficient, the measurement part of the operation consumed an ever-greater percentage of the total work required to produce a part. The development of automated "coordinate-measuring machines" (CMMs) in the 1970s helped somewhat, but measurement still used up about 50 percent of the total time required to produce a precision part.

It would be many times more efficient if the machining process could be made to produce accurate parts without being interrupted by the measuring process. Not only would it take less time, but fewer parts would have to be scrapped for being out-of-tolerance. (Some surveys have shown that in the U.S. one-third of the work force in manufacturing industries is engaged in re-work; that is, correcting out-of-tolerance parts made by the other two-thirds.) NIST research suggests that the problem can be solved by use of today's computer-controlled machine tools, because the position of the cutting edge of the tool is known and controlled at all times, at least in theory, by the computer. The computer can be programmed to compensate for known errors in the machine's movement, using sensors that feed back information on the machine's condition.

This concept of feedback and process control is well-known in some industries, such as oil refining and chemical production. In discrete parts manufacturing, however, it will require the development of a whole new generation of sensors and control systems. NIST researchers have already applied some of these ideas to commercial machine tools and improved their performance in terms of accuracy and control five to ten fold. Some of this research already is finding its way into the marketplace in new industrial machine controllers.

The automated "factory of the future" offers American industry an important weapon in the highly competitive world marketplace, but even for the largest firms the lack of agreed-upon standards for "interfacing" complex equipment is a difficult—and costly—problem. For close to 90 percent of the discrete parts industry—about 100,000 firms—the program is worse. These are much smaller companies (fewer than 50 employees) without great financial resources. Discrete parts producers, those who make products in small batches, are responsible for about 75 percent of the total U.S. trade in manufactured goods.

These smaller companies need to be able to buy automated machinery in stages, one or two machines at a time, and slowly build up to an integrated system. They need the flexibility to buy from different manufacturers at different times with the assurance that the machines they buy will work together properly without a lot of expensive, custom-designed interfaces. They need the same flexibility that one can now find when buying the parts of a home stereo system from several different manufacturers, knowing that they will all plug together. These firms also need a system flexible enough to switch from the production of one part to another quickly and without expensive reprogramming.

These are mostly problems of standardization—standard procedures, standard protocols, standard interfaces. The challenge is to develop standards which support current technology and yet still encourage equipment manufacturers to develop new and innovative products. These are problems that NIST is studying in the AMRF.

Three industrial standards have already been developed based on NIST automation research. For example, a standard method for exchanging graphics data between otherwise incompatible computer-aided design (CAD) systems, developed by a government-industry coalition led by NIST, was adopted by the American National Standards Institute (ANSI), a private voluntary standards organization. The standard now is supported by all U.S. CAD vendors which have at least a 1% market share.

NIST has recently established the National PDES Test Bed at the AMRF to support industry and government projects in developing and testing the Product Definition Exchange Specification (PDES), the next generation of data interchange standards for automated manufacturing. Recent demands for solid modeling, configuration control, fully computer-interpretable data, and interactive access by cooperating users have led to the need for PDES, one of the most ambitious standards ever attempted.

Implementing the new standard currently under development by voluntary standards organizations, industry, and government will require serious technical effort. Implementations must be tested as they are built to uncover problems and inconsistencies in the various definitions.

Experienced researchers working in a test bed environment such as the AMRF can identify potential problems and suggest clarifications and interpretations of the standard. Work in the AMRF on manufacturing data preparation has already developed a product part model which is consistent with the expected PDES standard. AMRF researchers are testing to determine the effectiveness of this part model as the information needed by the manufacturing applications in the facility. As PDES is developed, this effort will be expanded.

AMRF research also led to standards for the characterization of computerized coordinate measurement machines, and for a method of surface texture measurement. Seven other potential standards are now being considered by various industrial standards groups.

The AMRF is unique for many reasons, including:

- It's located at the National Institute of Standards and Technology. As an open federal laboratory with no commercial interests, NIST can make this facility accessible to private firms interested in automation research—-firms that individually could not afford such a complex research facility. NIST had a long history of working with private firms and organizations to develop standards and measurement and test methods that benefit the entire industry. That will continue under NIST.

- participation in the AMRF by industry, universities, and other government agencies. The AMRF has become a focal point for interactions among all American researchers in automated manufacturing.

- a wide variety of commercially available machine tools and robots. This is a direct result of the NIST decision to study the most practical, incremental route to automation for the small- to medium-sized firm; it is an approach that has never been used before.

- The flexibility of the system. One of the goals of the AMRF is to create a facility that is, in the jargon of the researchers, "data driven"—the actions of the various machines and robots should be determined primarily, or solely, by a computerized description of the part to be manufactured. This stands in contrast to modern "flexible manufacturing" cells which are truly flexible only for a limited "family" of parts for which the machine tools are programmed.

- Sensory interaction. The AMRF makes use of an unusually versatile robot control system in which sensory information from, for example, the NIST robot vision system is fed back to the controller to provide a basis for its decisions. This is important because it enables the system to react to its environment, eliminating the need for a lot of rigid programming.

- The scope of the facility. Research at the AMRF covers everything from the preparation of data on a new part to final automated inspection.

The AMRF is not a prototype of the "factory of the future." It is extremely unlikely that any actual factory would resemble the AMRF, at least physically. The AMRF is a laboratory for studying factory automation. Further, the AMRF is not a demonstration project. Although it does demonstrate several new and potentially important techniques for machine control and the integration of diverse systems, the AMRF is not a museum piece but rather a working research facility.

In addition to NIST funding, the Navy's Manufacturing Technology Program is a major source of support. Private firms and universities also contribute to AMRF research through the donation or loan of equipment or by providing personnel through the NIST Research Associate Program.

Generic Technology Development in the AMRF

The AMRF hierarchical control system is one of the most important generic technology innovations at this facility. It is flexible and can be adapted easily to new machines and new technology, works in the split-second, "real-time" world of factory processes, and is "modular," allowing today's manual or partially automated factories to evolve into factories of the future incrementally, adding one or two modules at a time. Several elements of the AMRF control system are being considered as possible factory automation standards by national and international standards organizations.

Key features of the AMRF control system include:

Hierarchical control –

The activities in a manufacturing facility, like most complex organizations, fall neatly into a hierarchical framework. NIST pioneered the use of hierarchical control in the design of a sophisticated robot control system a decade ago.

This work led to the development of a five-layer, hierarchical control model for an entire factory. The layers are Facility, Shop, Cell, Workstation, and Equipment control systems. Commands go into the hierarchy at the highest level, where a complex set of instructions is initiated. At each lower level, the instructions are broken down into successively simpler instructions. The bottom three levels which represent the shop floor control systems (cell, workstation and equipment control), have been implemented in the AMRF.

The AMRF represents what is probably a unique level of complexity in multi-level control systems. The modular, hierarchical software developed by NIST for this facility also is unique and serves as a model for future commercial systems.

The Cell –

The Cell Control System is the highest level of the AMRF hierarchy. It receives orders for parts from an operator terminal, determines the necessary resources, and then coordinates, and monitors the activities of the workstations required to manufacture the parts. It manages six workstations – three machining centers, a cleaning and deburring center, an inspection center, and a material handling system.

In conventional automation, a cell is a fixed set of machines — machine tools and robots — organized into a single manufacturing unit. Usually the cell is an actual physical grouping of machines, dedicated to producing a particular "family" of parts that have similar machining needs.

The AMRF control system researchers are using a more flexible concept of a "cell." Rather than a fixed grouping of machines on the factory floor, the cell exists only as a collection of data files and instructions in a computer. The cell can change its configuration, even the machines that are in it, in response to changing manufacturing tasks.

The computer emulation system —

Automated manufacturing facilities will not be static entities. New machines and corresponding control systems will be added from time to time. For this reason, it is essential to have a tool for testing the effects of these new systems before they are actually linked into the existing factory system. This testing must confirm not only that the new system has no internal errors, but also that its addition will cause no unexpected problems in synchronization.

These integration tests initially should involve none of the existing hardware or software in the facility, to avoid potentially catastrophic failures. The AMRF Hierarchical Control System Emulator (HCSE) has been a valuable tool for this work.

The HCSE is a real-time simulator designed to run control systems of the type used in the AMRF. The HCSE provides the programmer with a convenient framework for creating modeling programs to take the place of any element in the AMRF, from controlling computers down to individual machines or robot carts.

To the rest of the control system, the computer emulation "looks the same" as whatever it replaces. So when research needs dictate, any piece of equipment or group of machines or subsystem can be taken out of action and replaced by the appropriate emulation. Potentially risky changes to the control system can be tested without endangering expensive equipment. Versions of the HCSE are already being used commercially to study new automated manufacturing facilities.

Another important generic technology developed in the advanced manufacturing program is <u>information management</u>. In a very real sense, the cornerstone of the "factory of the future" will be information. The hardware of the AMRF — robots, machine tools and sensors — is very visible, but the ability to generate, store, retrieve and transfer information accurately and on time will be just as important as any hardware.

Such a facility requires a number of important advances in computer "software," including the development of standard techniques to "interface" different types of computer systems and software and the development of standard methods for handling data in an automated factory.

The interface problem in the AMRF is complex. At least nine different computer systems are in common use, ranging from large minicomputer systems to advanced microcomputers. At least eight different computer languages are used throughout the AMRF control system.

Special features of this unseen part of the AMRF include:

The use of distributed databases –

The AMRF approach to handling data is similar to the handling of machines – the user should be free to select computers and database software and still be able to build an "integrated" system.

Ideally, a factory control or planning computer should be able to request the information it needs without knowing which of several possible databases holds the information, or what format is used to store the data. The problem is complicated by the fact that the transfer of information in a factory must be done rapidly, without error, and coordinated with a host of other processes.

Creating a database system that meets the needs of the many different facets of an integrated manufacturing facility is an extremely complex procedure. AMRF researchers use sophisticated computer-aided software engineering tools to develop a logical model of the necessary data, check that all needed data is included in the model, determine the interrelationships of the data, and produce a prototype database.

AMRF researchers have developed a distributed database management system called the Integrated Manufacturing Database Administration System (IMDAS). IMDAS handles the administrative tasks of generating and storing new data, accepting requests for old data, locating and updating that data, and transferring the result. Control or planning programs in the facility need not know anything about how or where the information is stored, only how to make the request to IMDAS. IMDAS uses a "data dictionary" (to locate the required information), and a standard "language" to manipulate data and to make requests for data.

The AMRF data communications system –

The old idea of the automated factory as group of machines controlled by one huge central computer lacks flexibility. In the "factory of the future," computer processes such as control programs will run on many different computers, all sizes and models, possibly located in different buildings.

Such a "distributed" system requires a method of transferring information which is fast, accurate, reliable, and independent of the actual physical location of the machines. The transfer of information must also be done without interrupting the receiving machine, which may be doing something important at the time.

The AMRF uses the concept of computer "mailboxes," areas of shared memory on various computers to which all of the machines have access through the network communications system, subject to strict protocols. Communicating control processes can leave "messages" for each other and stop to read their own "mail" at opportune times without interrupting each other.

Currently, AMRF network communication uses broadband token bus with a proprietary protocol, broadband and baseband Ethernet with the DoD TCP/IP protocol, and point-to-point RS232-based communications with a locally-developed protocol. Work is underway to upgrade the AMRF network to one primarily based on the principles of the Manufacturing Automation Protocol (MAP) and the Technical and Office Protocol (TOP). One of the main reasons for building the AMRF is to have a testbed for studying the application of protocols such as MAP and TOP in the computer integrated manufacturing environment, and to use the results of that study in the standards development process.

Building an automated manufacturing facility like the AMRF involves much more than linking shop equipment together into a functioning system. An equally important generic technology development effort involves data preparation, or transforming the customer's requirements for a particular part into the production control data needed to manufacture that part.

These tasks include designing the part, determining what materials and tools are necessary to produce the part, developing the process plans that detail how the part is to be made, and generating the programs that instruct the robots and machine tools that actually make and inspect the part. Equally important is the need to verify these plans — to make sure that they don't instruct the machines to do something dangerous or impossible.

A common thread through all of these tasks is the need for standardized methods of handling the data.

Computer-Aided Design — CAD — systems are where the process begins. Ideally, once a part is designed on a CAD system, all of the information needed to develop the plans for making the part and verifying that it was made correctly should be in a standard, computer-readable format so that it can be used by the rest of the factory's control systems.

At present, however, CAD systems remain isolated "islands of automation" in industry. There is no standard method for passing the complete design information to the manufacturing systems that ultimately must use it.

At the AMRF, research is underway to determine exactly what sorts of data are required by a factory's manufacturing and inspection systems, and how these data can be generated automatically by the various data preparation systems in use in the facility.

The AMRF CAD facility includes four Computervision CADDS4X design workstations and a CADDS server (donated by Computervision, Inc.), all running on Sun Microsystems Sun-3 computers. The CADDS4X software includes solid modeling, NC coding, and engineering analysis tools in addition to the more traditional drafting software found on typical CAD systems.

Incoming part descriptions are converted to AMRF Part Model Files using commercial CAD systems and special software designed at the AMRF. The AMRF Part Model File includes 3-D geometric and topological information, tolerances, and other data on the part in a uniform format that can be used by other AMRF systems. An important project for the near future is the integration of these steps, and the conversion of the entire system to the new Product Definition Exchange Specification (PDES) data format.

Working from the Part Model File (later, from PDES files) and other information in the database system, operators then prepare "process plans" for the part. Process plans detail the actual steps—in their proper sequence— required to produce a part. Each level of the factory executes a process plan. In the AMRF, these computerized plans for a part include the cell's "routing slip," which is used to schedule the movement of materials and the assignment of workstations; the workstation "operation sheets," which detail the necessary tools, materials, fixtures, and sequence of events, and the machine tool's "instruction set," which guides the tool through the motions required to shape the part.

AMRF researchers are working to develop and test a single set of standard data formats for process plans at every level of the factory control hierarchy, and an editing system to generate, archive and update these plans.

Part of this effort involves the study of "expert systems" or other artificial intelligence techniques to generating the necessary process plans for each level of the facility. The Vertical Workstation already uses automatic process planning at two different control levels.

The "expert" process planning system is being developed on a Symbolics LISP Machine (using the LISP programming language) and on Sun Microcomputer Systems. It has been ported (functionally transferred) to a TI Explorer by industrial research associates from Texas Instruments.

A related problem is the design of intelligent inspection systems that can look up the design specifications for a part and decide what measurements are necessary to determine whether or not the finished part is within tolerances. The Inspection Workstation uses this procedure for inspecting parts made in the AMRF.

The Quality in Automation Project in the AMRF

Innovations in manufacturing technology are currently driven by demands to shorten product cycle time and to maintain a consistent, high level of product quality. These demands are generated by the high accuracy requirements of the defense and computer industry and by competitive market forces on industry to produce high quality products with a short lead-time. The main U.S. industrial competitor, Japan, exports products to the U.S. by selling quality. The United States must produce a quality product at a reasonable cost to reverse the trade imbalance.

One approach for the U.S. to meeting these demands is to implement a quality system that can monitor, measure, and then control, significant parameters in the manufacturing process. What is required is a quality architecture, strategies, and plans that will provide for a logical progression from the current product inspection and test methods, to a quality assurance system based on in-process verification methods. Not only will this process improve quality it will also reduce the number of defective parts that must be reworked or scrapped. It also has the potential for reducing or even eliminating final inspection, a process which does not add any value.

Applied to the metal removal type of manufacturing processes, the quality architecture incorporates three control loops. The first, and most responsive loop, is centered around the machine tool controller itself. This control loop is used to compensate for the systematic errors associated with the machine tool used in the process. These errors include, but are not limited to, the geometric errors of the machine tool caused by the inaccuracies in the machine tool components and in their assembly, and the distortions in the machine tool structure caused by thermal gradients. These systematic errors are determined by machine tool metrology, and characterized with respect to variables which can be monitored during machining. The resulting relationships from this characterization are stored in a quality control computer, or, for the next generation machine tool controller, in the machine tool controller itself. The relationships are used for predicting the resultant error and modifying the tool path in real time. The machine tool must be equipped with sufficient, and strategically placed, sensors to determine these errors as well as the errors associated with the cutting tool geometry. However, this technique cannot be used to compensate for parts specific errors such as deflection of the workpiece or the machine tool. To a large degree these errors can be minimized by the second control loop, which depends upon process-intermittent inspection of the part.

The second control loop uses the machine tool as a measuring device to determine the geometry of the part being made on the same machine. A number of methods can be used either by themselves or together. For example, mechanical probing or ultra-sonic dimensional measurements can be used to determine the dimensions of the part before final machining. During the final machining, the part program is altered or "skewed" based on the inspection information. In order to reduce the amount of non-productive inspection time, the entire process must be performed in as short time as possible.

The third, and the final control loop involves a post-process inspection of the part. The part is measured on a coordinate measuring machine and the deviation from a perfect part is determined as well as the cause of the deviation. This information is then used to alter the parameters used in the first and the second control loops. Then the control loops are tuned based on the post-process inspection information. As the control loops are tuned, the accuracy and the quality of the part improves, and post-process inspection can become a tool for process verification rather than part inspection, and used less frequently if at all.

While the application described is for machine tools, the architecture and techniques can be applied to any discreet small lot size operation.

The Composites Workstation at the AMRF

The increasing use of composite materials in Navy platforms has led researchers in the AMRF to extend their work to those materials. Working with industry and university researchers and with one of the newly founded NIST Manufacturing Technology Centers (MTC), AMRF researchers are developing an advanced manufacturing workstation to fabricate composite parts. Initial research at this Composites Workstation will focus on automated composite fiber placement using robotic systems.

The architectural, control, and information handling principles developed in the AMRF and tested in metal-working applications on the shop floor will now be tested for a broader range of processes.

Research at the Composites Workstation will begin as a joint program involving the Center for Manufacturing Engineering's Robot Systems and Automated Production Technology Divisions, the Institute for Materials Science and Engineering's Polymers Division, the North East MTC operated by Rensselaer Polytechnic Institute, Automated Dynamics Corporation, and SRI International.

Two technologies previously developed at the AMRF will serve as major resources for this work. CAD (computer aided design) - based off-line programming, originally developed at the AMRF's Cleaning and Deburring Workstation, will be used to generate robot trajectories automatically, and the NIST Real-time Control System (RCS), a foundation of the AMRF, will be used for sensor-based control.

Conventional filament winding technology requires that parts be symmetric about an axis of revolution. At this new workstation, a special end-effector mounted on the robot will place composite fibers fed from a spool on a mandrel. The mandrel will represent the shape of the final part and may be stationary or have one or two servoed axes. The placement of the fibers will be determined from part geometry and the part's structural design. Use of this fiber placement technology will allow the fabrication of complex parts.

At the AMRF's Cleaning and Deburring Workstation, the CAD-based off-line programming approach used part CAD data and a knowledge of the workstation layout to generate robot trajectories for deburring and part handling automatically. A similar approach based on composite part geometry and the required fiber placement orientations will be used at the Composites Workstation to generate the robot and mandrel motions automatically. Researchers believe that having a mandrel with one or two axes of motions which can be coordinated with the movement of the robot will permit not only the fabrication of more complex parts but also the simplification of end-of-arm tooling. To provide this coordinated movement, the RCS will be used to control both the robot and the mandrel.

Machine vision and fiber tension measurement sensors will be used to monitor and adjust fiber placement. An important feature of the RCS is that real-time modification of robot and mandrel motions can be made based on sensor data.

Fabrication of parts made from both thermoset materials, which require autoclave curing to bond, and thermoplastic materials, which can be "welded" in place as fibers are positioned, will be studied. General areas of research related to this work will be control of torch parameters during thermoplastic welding, process monitoring of autoclave curing of thermoset materials, inspection techniques for verification of proper fiber placement, and NDE techniques for evaluation of part consolidation. Other work will be done on determination and repair of damage in composite structures.

Transferring AMRF Technology

The Research Associate Program mentioned above is only one of the ways that NIST research results are transferred out of the AMRF. Another approach to transferring this technology is through the establishment of the Manufacturing Technology Centers Program at NIST. The objective of this program is to accelerate the transfer of advanced manufacturing technology to small and medium-sized U.S. businesses to assist these firms in improving their manufacturing and process capabilities and market competitiveness—an important ingredient to successful international economic competition. Each center will apply advanced manufacturing techniques to the needs of manufacturers located within its region. The advanced technologies transferred will emphasize those developed at the AMRF. Each center is expected to communicate its experience to all interested parties.

A center should become a mechanism for accomplishing significant results more effectively and in a more timely manner than would be possible without NIST financial support. NIST support is intended to complement, not substitute for, center operating funds derived from state and local government agencies and from other sources.

The transfer of advanced manufacturing technology is the primary task of this program, rather than the performance of research. Activities of each center are expected to include: 1) informing and educating the industrial firms in its region about advanced manufacturing techniques; 2) demonstrating the applicability of advanced technology to these firms; 3) actively assisting firms in evaluating their requirements; 4) assisting with the implementation of desired applications; 5) supporting workforce training and retraining; and 6) communicating technology transfer experiences to a wide national audience.

One exciting aspect of this new program is that it represents the first time the federal government explicitly recognized the need to establish an intermediary between the federal laboratories that perform research and development in new technological areas and the small- and medium-sized manufacturing firms that hope to benefit from the availability of this technology.

It has long been a maxim that technology transfer is a body contact sport. At NIST, our successes in transferring technology have generally been a result of cooperative research agreements in which staff of some firm spend up to a year working side-by-side with our staff solving some problem of mutual interest. Some of these agreements also entail a donation of some piece of equipment to the AMRF. In these cases, the research program will typically involve incorporating the equipment into the AMRF. At the end of these cooperative research programs, the visiting staff return to their organizations, taking with them the knowledge of advanced manufacturing techniques developed in the AMRF.

This technology transfer process follows the "body contact" paradigm closely, and has worked well for NIST over the years. Unfortunately it only works well for large firms, with a large enough staff that they can afford to send one or two staff members to NIST for an extended period of time. Obviously, this is not the case for most of the small and medium-sized manufacturing firms in this country. This is the motivation for the establishment of regional centers to serve the needs of the manufacturing firms in their region by working closely with them to identify technological improvements that can help these firms improve productivity and therefore maintain or gain market share. These centers must serve as more than just brokers, however. It is also their responsibility to help increase the flow of technology out of federal laboratories by identifying technologies that can benefit industry, and where necessary, extracting that technology, refining it, packaging it, fine tuning it, and otherwise making it available and usable to the general public. This step is important because it is not the mission of the federal laboratories, including NIST, to engage in product development. This manufacturing Technology Centers Program at NIST is unique. It builds on the resources of NIST and other laboratories while establishing a mechanism to combine the push of new technology development with the pull of manufacturing competition for market share.

Three organizations have been selected to become the first NIST Regional Manufacturing Technology Centers: The Great Lakes Manufacturing Technology Center at the Cleveland Advanced Manufacturing Program in Cleveland, Ohio; The Northeast Manufacturing Technology Center at Rensselaer Polytechnic Institute in Troy, New York; and The Southeast Manufacturing Technology Center based at the University of South Carolina in Columbia, South Carolina. NIST has now established cooperative working arrangements with each of these organizations.

SMALL-SCALE ADVANCED MANUFACTURING

Background

As discussed above, the goals of the Automated Manufacturing Program of the Center for Manufacturing Engineering have been two-fold; to develop the Quality Control technology for the fully automated environment, and to encourage the writing of interface standards that would make automation technology accessible to small discrete part batch shops by allowing for incremental application of this technology. To further these goals we constructed the Automated Manufacturing Research Facility. The AMRF was planned to be a full scale model of a machine shop of the year 2000 and was to be completely unmanned. During the course of construction we learned many things, including the following.

- The technology commercially available in 1987 would not support fully unmanned operation. The AMRF contains, of necessity, many subsystems that were developed at NIST because they are not yet commercially available.
- The current generation of machine tool controllers make integration at the workstation or cell level very difficult. Even second generation controllers that provide some interface capability are unsatisfactory.
- Without further development, the current generation of robots are neither dexterous nor reliable enough to support on-machine fixturing and chip management. Also, robot controllers currently lack programming capabilities.
- The small machine shop operators, who make up 87% of the 130,000 firms in the small-batch discrete part industry, are only interested in commercially available equipment that is sold turn-key, is supported by local interests, and has been demonstrated to be cost effective under conditions very similar to theirs.
- The most effective way for the Center for Manufacturing Engineering to make advanced manufacturing technology accessible to small industrial users is by cooperative efforts with the vendors of the means of production.

Much of this information is not surprising since we are some years ahead of the time when AMRF technology was expected to be common.

Operating the NIST machine shop, the Fabrication Technology Division, during the time that the AMRF was under construction also was a "learning experience." Inspired by a compulsory A76 (outsourcing) evaluation, we discovered by cost studies that the most immediate source of cost savings was in improving the "business" aspects of shop operation: scheduling, material resource management, time-keeping and billing. We discovered that these activities are also responsible for a large portion of the delay between receipt of order and delivery in our system.

The circumstances in the outside world have also changed during the time of the construction of the AMRF. With the introduction of the 8086, 80286 and most recently the 80386 and 68000 computer chips, Desktop Computers now have capabilities only available on mini-computers at the time the project was started. These capabilities are now beginning to be exploited for quite respectable CAD systems running on Desktops. Moreover, at least one major computer supplier working in cooperation with machine tool builders and manufacturers of machine tool controllers has introduced interface boards establishing, at least a degree of communication between PCs and machine tool controllers, which would appear to reduce the interface problems at the Workstation and Cell levels.

Moreover, when the Center for Manufacturing Engineering started the construction of the AMRF, NIST was almost alone in addressing the discrete batch part sector of the economy. Now, of course, the machine tool industry, which is both a part of and the infrastructure that supports that industry has become a Presidential concern and the subject of National Security Decision Directive Number 226. This Directive identifies a series of initiatives to facilitate modernization of this critical national industry. NIST is, through the Department of Commerce Domestic Action Plan, committed to contributing to this effort. Competitiveness has become a National Priority and several Bills are now before Congress proposing national efforts in automation.

The AMRF-based research, despite having significant impact on larger high-tech organizations (South Carolina Research Authority and the Navy Man-Tech programs), and being a vital contribution to the factory of the future, will have relatively little impact on small enterprises unless a concerted effort is made to transfer AMRF technology to them. One example is that portion of AMRF technology which is now commercially available in a turn-key package that includes not only the vertical integration of the hierarchical control system, from design to machine code, but also the horizontal integration from receipt of order to dispatch of billing.

With the aid of industrial partners, without which the program is not viable, the Center proposes to make a serious effort to make available such a package.

The Questions

Small job shops — operations with fewer than 50 employees — make up about 85 percent of U.S. metal fabrication facilities and account for about 75 percent of all U.S. metal fabrication. They are running substantially behind their overseas competitors in the use of modern technology. In Japan, for example, approximately 30 percent of all machine tools are computer-controlled; in the United States, fewer than 11 percent. Sweden and West Germany also have more computer-controlled equipment than the United States.

What modern technologies are commercially available, affordable, and useful to the small job shop? How are they best introduced? What return on investment might be expected? To help answer these questions, NIST is using its own job shop to conduct an experiment in the practical implementation of computer-integrated manufacturing.

The Experiment

The NIST Fabrication Technology Division (FTD) is a good example of a small job shop. The division designs and manufactures specialized instruments and other equipment for the NIST laboratories. The workload is comparable to that of many small job shops in high-technology industries. FTD employs just over 50 people in its main shop and several on-site contract shops, using a wide variety of numerical-control (NC) and manual machine tools of varying vintages. Other duties include tool and material inventory and management, cost estimating, and billing.

Beginning in July 1988, FTD began a project to modernize and improve its own operations, creating the "Shop of the '90s." In order to make the project relevant to small, private-sector job shops, advanced experimental hardware and software from the NIST laboratories would not be used, only affordable, commercially available "off-the-shelf" systems and software. Purchases and changes were justified by a reasonable return on investment.

The project involves three stages:

- Conducting a thorough review and evaluation of existing machine tools and resources to provide a basis for decisions to repair or replace existing tools, and to allow more accurate estimates of return on investment.
- Installing a personal computer network to support computer-aided cost estimation (CACE), computer-aided process planning (CAPP), computerized tool room management, and computerized job and job cost tracking. In addition, design and manufacturing (CAD and CAM) systems based on personal computers were added to speed design and programming of parts.
- Training shop personnel in the use of the new systems and equipment. The training program is structured so that the most experienced personnel—with the shortest learning curves—are trained first. Ultimately all shop personnel will be trained to use all the machines and computer systems in the shop.

Role of the Center for Manufacturing Engineering

- Provide "neutral" ground for planning and coordination efforts of industrial partners.
- Provide input, based upon AMRF experience and contacts with small enterprises and their associations, to definition of AMRF system requirements.
- Provide access to and help interpretation of the AMRF experience base and any software modules that may prove useful.
- Provide test site, within the Fabrication Technology Division where systems and sub-systems can be tested making use of available craft and professional personnel.
- Make use of all existing NIST Technology Transfer programs to encourage the adoption of the technology by target groups.

Role of Industrial Partners

Based on the needed technical skills, the plan envisions at least three industrial partners. More than one of these partners may in fact be a single organization, or several organizations may desire to cooperate with each other or independently pursue a single role. The skills needed are:

- Detailed knowledge of Desktops and their operating systems
- Detailed knowledge of Machine Tool Controllers

- Detailed knowledge of Desktop software especially CAD and shop management systems.

The role of these partners will be to :

- Work with NIST in developing system requirements that meet a useful fraction of the needs of a small shop and at the same time are within the capabilities of available Desktops and at least some Controllers.
- Assemble from existing components a prototype system that can be installed in the Fabrication Technology Division of NIST for testing.
- Assuming the tests are successful, be prepared to have system commercialized for wide adoption.

The Results

FTD has worked with nine nationally recognized vendors of hardware and software to create the "Shop of the '90s." By the end of September 1989, FTD will have in operation a computer-integrated manufacturing system geared to the small job shop. The system will include computerized cost estimating, process planning, tool room management, design, and manufacturing.

The project has already demonstrated a three-fold reduction in NC programming time and, because of improved productivity, a 6-month payback time for new equipment (based on FTD costs, workload, and calculations).

NIST does not recommend particular products or suggest that the products used in the "Shop of the '90s" are the best for any other machine shop, but the principles and procedures developed in the program can be useful to many small shops. FTD staff have begun an active program to inform private firms of the results of the "Shop of the '90s" experiment. Talks and seminars are scheduled routinely both at NIST and around the country. Tours are given on a regular basis.

By the fall of 1989, FTD will have in operation a "Shop of the '90s" training center, which replicates the FTD equipment and software on a small scale. The training center will be made available to private-sector industry and shops for use in cooperative research programs, to test the compatibility of different software packages, and similar tasks.

The Competitive Issue

The U.S. is losing its world market share in manufactured goods. A perception exists that American industry cannot produce a quality product at a competitive cost and within a competitive time frame. The U.S. still leads in new product concepts arising from applied research—at least through the first prototype. After this, when the commercialization process truly gets underway, we seem to falter.

The weak link in the chain from customers' needs to marketable products would seem to be toward the production end; but in fact it is right at the beginning, in our design practice. U.S. design is often inefficient, detached from the production process, undocumented in terms of the rationale for design decisions, and production-facility dependent.

However, there exists a method that has been demonstrated to improve the design process. Documented use of the method has produced a reduction of 50% in the number of engineering design changes, a reduction of 40-60% in the total product development time, a reduction of 30-40% in the manufacturing costs, and a reduction of 75% in the scrap and rework of manufactured products.[2] The method is called "product data-driven engineering" or "concurrent engineering." It is a systematic approach to the integrated, concurrent design of products and their related processes and materials, including manufacture and support.

It is possible to accelerate the use of product data-driven engineering by U.S. industry by capitalizing on the American edge in information technology. Fortunately, the critical ingredient to the use of concurrent engineering is the integration of product and process data. This integration, which is a concern of information technology, gives the designer, along with everyone else in the commercialization chain, data about the entire life-cycle of a product and how their decisions affect all other phases of the product life-cycle.

Manufacturing will be revolutionized by the establishment of a world recognized standard for the integration and the exchange of product and process data. Such a standards effort is already underway and is called the "Product Data Exchange Specification" (PDES). The effort is extremely ambitious. The ultimate goal is the creation of a standard that will represent all the information about all types of products (mechanical, electrical, etc.). PDES addresses the questions: What does the product look like? (e.g. geometric features); How is it constructed? (e.g. materials and assembly); For what function is it intended? (e.g. structural properties); How do we know it works? (e.g. tolerancing); and, How is the product development managed? (e.g. bill of materials). An important aspect of the standard that is

2 Winner, R.I., Pennell, J.P., Bertrand, H.E., and Slusarczuk, M.M.G., "The Role of Concurrent Engineering in Weapons System Acquisition," Institute for Defense Analysis Report R-388, December 1988, p. vi.

not yet being addressed is how this data can be represented so that knowledgeable decisions can be made through all phases of the commercialization and the life-cycle management of a product.

Product data-driven engineering, and other aspects of the technological environment represented by PDES, will be the revolutionizing factor in the ongoing evolution of manufacturing that began with the introduction of computerized design and intelligent machines, combined with intelligent processing. Product data-driven engineering will link together design and all other portions of a product's life-cycle. Product data-driven engineering will provide the means of storing and communicating intelligence on products and on all processes that occur during product life-cycles. Product data-driven engineering is the key to producing top quality products at competitive prices within a competitive time frame.

The Technology

At present, most product and process development is done at different contractors' facilities, making it is difficult to share the knowledge of how best to produce a particular product. Typically, over the life of a product, many different companies are involved and must interact. In addition, information systems do not yet exist there have the capability to automatically capture the knowledge that is being generated as the product life-cycle processes are actually occurring.

The solution to the problems related to designing, commercializing and managing a product over its life-cycle is the ability to capture the knowledge gained during these processes and to exchange that knowledge among different computer systems. The knowledge can then be used by the designer and by everyone else involved in managing the product's life-cycle. For example, knowledge about how a product would be processed or what new materials would be required to meet the functional specification is made available to the designer to ensure the best quality product is designed. In addition, knowledge about the functionality and design of the product is made available to the down-stream life-cycle managers as the design is being developed so that the most appropriate and cost-effective materials and processes can be used.

It is the development of a shared database environment to capture the knowledge required to manage a product throughout its life-cycle that will enable U.S. industry to take advantage of a concurrent engineering environment. The intelligent machine and processing system cannot exist without a shared product database for managing the product and process data.

There are many technical issues that must be resolved for such a database system to be implemented. An interface must be built between the present computer-aided-design representation of a product and other computer-aided systems, such as computer-aided engineering (i.e. analysis) and process planning. The production costs and capabilities must be integrated into the database. The intelligent systems must have access to the geometry data in much the same manner that users query business systems. Finally, there must be a mechanism for allowing new knowledge to be added to the database as the intelligent materials processing operations are being performed.

The technical challenge is the development of the information technology and the associated standards that will define the environment for the representation of product knowledge and will allow the implementation of a shared database environment for concurrent engineering.

The Role of the Center for Manufacturing Engineering

The product knowledge representation, its associated information-technology implementation, and the needed PDES standardization effort require the presence of a technically competent "neutral agency" that can work effectively with a wide range of organizations. NIST is that agency, and within NIST CME is in a unique position to contribute new laboratory discoveries because of its Automated Manufacturing Research Facility, a flexible manufacturing laboratory that already contains a level of intelligence and a shared database system. This environment can be readily expanded to explore the research issues associated with product knowledge representation and a "knowledge database."

In addition, CME already serves in a key role as the secretariat for the IGES/PDES organization that is the lead in developing a PDES standard. Also, there already exists within CME, a National PDES Test Bed that is being used to test PDES implementations. This test bed can also be utilized in the development and testing of PDES in an intelligent machines and processes environment.

The CME Engineering Research Paradigm

In recognition of the key role of information management in the development of engineering systems, CME developed the "Engineering Research Paradigm" as a model for the appropriate CME role. The Engineering Research Paradigm consists of four components: (a) system specification, (b) information management technology, (c) engineering technology, and (d) engineering application. The paradigm is applied where there is an industrial need for which it is appropriate for NIST to have a role. The major task is for CME to lead the industrial community in the development of a new set of standards that will result in the production of world-class products. The standards include an information model that represents the product data requirements, and a functional model that represents the architecture needed to implement new technologies related to the desired application.

In addition to standards, CME outputs include technology concepts that are transferred to industry through publications and personal interactions. Products may be produced in CME engineering application laboratories, but these products are prototypes that serve to create credibility in the research through proof-of-concept demonstrations. The laboratories become models for specifying the research environment needed to study the concepts and architecture developed in information management and engineering technology activities.

The combination of the need for advances in product data-driven technologies and the need to represent engineering data in a standard format (PDES) is a perfect industrial problem that can be addressed using the CME Engineering Research Paradigm.

The four components of the CME engineering research paradigm as it applies to PDES and Product Data-Driven Engineering are as follows:

For the product data-driven engineering application, system specification is the development of the PDES standard as an International Standards Organization data exchange standard (that will be known as "STEP") and the implementation of application protocols that specify the engineering environment in which PDES will be used.

Information management technology is the conversion of PDES into an information management system that can support the engineering requirements. The technology falls into the areas of information modeling, data dictionaries, and database management systems. Important tasks that must be accomplished involve (a) developing an overall "framework" that integrates the three information technologies, (b) implementing the appropriate information systems that are based on the framework, and (c) assuring the successful use of the framework by its acceptance as an international standard.

Engineering technology is the development of technologies that represent the processes within product data-driven engineering. The life-cycle engineering system represents an integrated set of individual functions: design, planning and programming, production, deployment, operation, support and maintenance, and recycling and recovery. The information required to create and evolve the product and the manufacturing processes is represented by PDES. The challenge is to develop the application protocol interfaces between the PDES knowledge base and the life-cycle processes.

The laboratory in which the architecture and concepts developed in the information management technology and the engineering technology components are implemented is the expression of the application technology. Laboratory facilities within which product life-cycle processes can be carried out are used to test the technology concepts.

The CME Program

A critical component of the development of a PDES environment is the ability to define and test specific PDES applications and implementations. The National PDES Test Bed, already under construction at NIST, will be expanded to address the bigger issue of applications of intelligent machines and processes. The test bed will become a model for future test beds that will be established throughout the world. The test bed will also serve as a model for software and hardware configurations and personnel resources needed to test and implement PDES.

The CME program will center around the construction of a complete facility for research and development of technologies relating to product knowledge representation. The facility will rely on the AMRF as the manufacturing component. A new design laboratory will be added and interfaced to the AMRF. The experience gained from the actual experimentation with product knowledge will serve as the basis for CME to provide results to the PDES standards community.

In addition, CME proposes to perform research in appropriate knowledge representation methodologies that can be incorporated into the PDES standard. CME will work with the standards community to include the results of this research into future versions of the standard. CME will develop methods for the verification, validation, and conformance testing of the resulting standard.

Based on the formal knowledge representation developed for the standard, CME will perform research to build the necessary information technologies for managing product knowledge. This includes the development of a new framework for a knowledge-database environment that can handle effectively the knowledge as it is created, captured, and used during product life-cycle processes. This knowledge database framework will have the capability of capturing also the constraints and behavior of the various processes and parameters involving the product and of embedding this information in data structures. Research will be needed for such areas as distributed database systems, knowledge databases, data dictionaries, and information modeling methodologies. This research effort will lead to numerous new standards in information technology that relates to the requirements for a knowledge database.

In parallel with the development of a knowledge database, CME will perform research into the development of design as a formal science and methodology. This will include the definition and development of a framework of tools and models to be used during the product life-cycle. Such tools and models include: (a) process models, (b) materials models, (c) cost models, (d) system models, (e) design of experiment and other statistical design methods, and (f) models for the design process itself.

The Economic Impacts

This expanded program will provide the product and process knowledge, system framework, and standards to enable U.S. industry to design and manufacture products at competitive market costs with minimum delay between concept and marketing. It will lead directly to the design of the "knowledge database" needed for the use of intelligent machines and processes across a broad spectrum of industries. It will improve productivity, reduce costs, and re-establish the clearly dominant position of the U.S. in the manufacturing world.

Objective

The objective of the proposed NIST program will be to develop performance criteria, measurement methods, and standards for intelligent machines that will speed the development and use of this technology and facilitate transactions between buyers and vendors in the marketplace.

Background

Intelligent machines and processes are systems that consist of:

- Sensing devices that measure the environment.
- Perception mechanisms that extract from sensed data information about objects, events, states, and spatial and temporal relationships in the world.
- Knowledge representation of the world, including knowledge of materials, processes, and parts.
- Planning mechanisms that select goals and decompose them into low level actions.
- Actuators that operate on materials and parts, producing a product.

These are all embedded in a system architecture that coordinates their respective actions.

An intelligent machine or process can be thought of as a plant which operates on materials and parts. This plant may be a robot, an automatic factory, a materials processing plant, or bioengineering facility. Products produced may be discrete mechanical or electronic parts, or materials in solid, liquid, or gaseous form. An intelligent machine may also be a vehicle that accomplishes some task of transportation, exploration, or weapons delivery. Intelligent vehicle systems use object and terrain databases to generate process plans and control programs.

The development and growing use of intelligent machines and processes is affecting industry, commerce, defense, and the quality of life for all people.

Current industrial robots and computer controlled machine tools for manufacturing are only the first generation of a whole family of intelligent machines. Future intelligent machines will possess off-line programming, sensory capabilities, and adaptive behavior that will allow applications in uncertain and hostile environments such as construction, mining, undersea resource exploitation, shipbuilding, space, and the battlefield.

These applications will require extension of current control theory to cope with planning, the extension of artificial intelligence to deal with real time constraints, and the integration of these technologies into real-time, sensory- interactive control systems capable of performing complex tasks in an uncertain and possibly hostile environment.

Each of the elemental components of sensory processing, world modeling, and task decomposition is relatively well understood. What is lacking is a formal theory and an open system architecture with standard interfaces so that all of these elements can be integrated together into intelligent machine systems. Open system architectures, interface standards, and performance measures, all based on a solid theoretical framework, would significantly speed the development of intelligent machine systems technology for commerce, industry, and defense.

The proposed NIST program will develop the theory and technology base necessary to establish standards for, and measure the performance of, future generations of intelligent machines and processes.

Potential Impact

Intelligent machines represent a fundamentally new technology, potentially as important to civilization as the invention of the steam engine or the discovery of electricity. Intelligent machines and processes will have a profound impact on the cost and quality of most manufactured products, materials, commercial buildings, homes, utilities, and transportation facilities. They will be economically important in mining, undersea drilling, space exploration, and the service industries. They will be militarily significant on the battlefield.

Current automation technology already has had an economically significant effect on the manufacture of automobiles, appliances, electronics, computers, drugs, machine tools, and aircraft. This represents only the beginning of a new industrial revolution.

In the future, factories, construction sites, mines, underwater drilling platforms, space stations, and battlefield weapons will all make extensive use of intelligent machine systems. Computers will control machine tools, material transport systems, assembly machines, finishing machines, inspection systems, packaging and shipping systems. On future construction sites, mines, and drilling rigs, machinery will be driven from databases that completely describe the terrain and the structures to be built or serviced.

Role in Promoting U.S. Competitiveness

The nation that leads in the development of intelligent machine technology will very likely lead the next industrial revolution. Without more aggressively exploiting intelligent systems technology, the U.S. will be at a competitive disadvantage in international markets.

International competition is strong. The U.S. balance of trade in manufacturing has declined dramatically over the past decade, to the point where it has become a major problem of national concern. This decline is in no small part due to the more aggressive exploitation of intelligent machine technology in Europe and Japan.

The U.S. construction industry's international market position is also rapidly eroding. Between 1982 and 1986, overseas contract awards to U.S. firms declined 50 percent. U.S. firms won only $22.8 billion in business during 1986, a 21.4 percent decline from $29 billion in 1985. A recent study by the Congressional Office of Technology Assessment (OTA) attributes the decline in international competitiveness of the U.S. construction industry to four factors, one of which is "development of innovative construction techniques by competing European and Japanese companies." OTA warns that a weakened international U.S. construction industry will lead to increased foreign competition in the U.S. as well as in the world market.

Both Europe and Japan are aggressively pursuing applications of intelligent machines technology. The European Strategic Program for Research and Development in Information Technology, ESPRIT, is a 10 year effort begun in 1984. During the first 5 years a $1.5 billion research effort was conducted concentrating on the technologies of microelectronics, information processing, and computer integrated manufacturing and office systems. During the next 5 years the ESPRIT program is planned to double in size, with a budget of about $750 million per year.

The Program for European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS), is a research project to develop technology for intelligent automobiles and highway systems. A seven year budget of over $700 million is directed at applications of intelligent machine technology to the driving environment with the goal of reducing accidents attributed to driver error and increasing the efficiency of road traffic.

The Japanese have similar programs of comparable size to both ESPRIT and PROMETHEUS. In addition, the Japanese currently lead the rest of the world in the application of robotics to manufacturing. The government of Japan is currently funding robotics research at about $130 million per year. The Japanese are also aggressively transferring robotic technology to undersea and construction applications. A recent DoC study on Mechatronics (the Japanese term for Intelligent Machine Systems) found that the U.S. is trailing Japan in every relevant technology, except for advanced software.

The proposed NIST intelligent machines initiative will provide technical support to help U.S. industry retain its lead in advanced software, and recapture the overall competitive advantage in manufacturing and construction that the Japanese and Europeans have recently acquired and are now rapidly expanding.

NIST Role

NIST will perform basic research, develop a formal theory, define an open system architecture, develop performance measures, test proposed standards, and work with voluntary standards committees to get national and international standards adopted for intelligent machine systems.

Program Description

The proposed program will build on existing NIST work in advanced robotics and intelligent machines for manufacturing, structural engineering, construction, mining, autonomous undersea and land vehicles, SDI battle management, and space telerobots.

The program will:

- Conduct basic research in the fundamental science of intelligent machine systems and perform experiments in machine vision, sensory fusion, knowledge representation, decision theory, intelligent controls, mechanical systems, adaptive and learning systems, design databases, and software engineering.
- Develop a formal theory of intelligent machines and a set of methods for measuring levels of intelligence. These include both theoretical (mathematical, logical) and empirical (performance) measures.
- Build a facility for conducting experiments and evaluating the performance of intelligent machine systems for manufacturing and construction applications. This facility

will include computer systems for sensors and measuring devices, mobile robots, control systems, and software development and testing environments. The facility will be used to develop and test open systems architectures, define performance measures, and evaluate proposed standards. NIST will work with voluntary standards committees to get national and international standards adopted for intelligent machine systems.

Planned Accomplishments

A Formal Theory –

Perform basic research in sensory processing, knowledge representation, and intelligent controls. This research will develop the new knowledge needed to define a formal theory of intelligent machines and processes.

Standard Reference Model Architecture –

From the formal theory, develop a standard reference model open systems architecture for intelligent machines and processes. This will provide a guideline for the specification, design, construction, and procurement of intelligent machines and processes. It will also enable researchers to focus on well-defined scientific problems within their area of expertise (such as image flow, tactile sensing, real-time planning, control theory, learning systems, etc.) with an understanding of how their work integrates into the larger context of an intelligent system.

Measures of Performance –

Use the formal theory of intelligent machines and processes to develop quantitative measures of performance including a set of methods for measuring levels of intelligence.

Commercial Implementation –

Work with industry to build a commercial version of an intelligent control system based on the standard reference model. This would include both hardware and software. A commercially available intelligent control system could be used by industry, government, and university research and development labs for a wide variety of intelligent systems applications.

Interface Standards –

Develop a draft set of interface standards for intelligent machines and processes. This will facilitate the incremental implementation and upgrading of intelligent machines and processes. Interface standards will promote competition and rapid commercial development because they will make it possible for various vendors to provide different components for intelligent machines and processes.

Laboratory Facility –

Establish capability at NIST to evaluate the performance of intelligent machines and processes for manufacturing, materials processing, and biotechnology applications. This will allow experiments to be performed to test and verify the formal theory of intelligent machines and processes and the open system architecture based on it. It will also facilitate the application of intelligent systems technology to the economically important areas of manufacturing, materials processing, and bioengineering.

The Competitive Issue

In its support of precision-engineered systems vital to U.S. industries, an area of special concern to CME is that of manufacturing involving the fabrication of nanometer-scale structures (i.e., those with features measured in billionths of an inch), such as in the machining of nano-scale mechanical components and the lithographic-production of nano-scale electronic devices. Identified in the new DoC Emerging Technologies report as an area of scientific opportunity, nanotechnology includes a new type of manufacturing of major commercial significance and fierce international competition; it is also a type of manufacturing that requires broad advances in metrology by NIST to support effectively.

To remain competitive in the global market for micromachines, advanced robotics, information technology, exotic materials, and future computers, U.S. industry must develop forefront technology and new manufacturing processes for producing devices of increasingly smaller sizes, ultimately at atomic and molecular sizes—a nanotechnology. Such miniaturization is motivated by the recent demonstrations of sub-microscopic mechanical devices and needs in microelectronics to increase the number of devices on a single chip, thereby lowering the manufacturing cost per device and greatly increasing chip and overall system performance. Sub-microscopic mechanical devices have the potential to create a revolution for mechanics similar to that experienced by electronics during the 50's and 60's. In electronics, billions of devices and trillions of storage elements on chips no larger than a dime are forecast with great potential for application to intelligent data bases and desktop sized massively parallel processor computers.

Industry experts, worldwide, agree that present miniaturization processes and devices will run up against fundamental limits by the early 1990's; limits that will require new species of devices and new manufacturing processes. The road to the ultimate miniaturization will, therefore, be a combination of materials processes, devices and systems which are evolutions of current approaches and revolutionary processes based on molecular designing and engineering, revolutionary quantum well and box devices, and radical new computer architectures such as neural networks and cellular automata. To keep up with the rapid worldwide evolutionary pace and to provide support for revolutionary developments, U.S. industry will have to become much more sophisticated in all aspects of nanotechnology and all its associated enabling technologies that are being developed to cope with the special problems resulting from the extreme reductions in device size.

The Technology

Almost thirty years ago the physicist Richard Feynman explored the problems and wonderful possibilities of being able to manipulate and control things on a scale sufficiently small to involve operations with individual atoms and molecules. His basic question was; what would happen if we could arrange atoms one by one the way we want them? He argued that with such a capability, and within the laws of physics, all the books written in human history, some 50 million volumes, could be encoded and stored in a volume less than that of a speck of dust, mechanical systems as complex as an automobile could be reduced in size by over 4000 times, exotic new materials with checkerboard arrays of atoms and layered structures could be synthesized upon order, and molecular computers with biological-like capabilities for image processing and memory storage could be built. The dream lay relatively dormant for many years, but as our tools have developed, particularly over the last ten years, interest has grown to such a level that there is currently a worldwide boom in activity in nanotechnology to pursue many of the goals discussed by Feynman.

Nanotechnology is the machines, devices, materials, and processes as tools used to make devices whose functional properties depend on structural features which are 0.1 to 100's of nanometers in size. To quote a recent Washington Post article on microengineering, this is the domain of, "....nanometers, or billionths of a meter, where bacteria loom as large as tug boats and a human hair becomes a mountain range." It is a technology primarily concerned with manipulating and controlling things at atomic and molecular dimensions; where the production of new materials and devices is bounded only by our imagination and the basic laws of molecular interactions and geometry; where electronic, mechanical, and optical devices, at anticipated limits of miniaturization, will be made of complex engineered molecules rather than bits of solids; and where electrons can be trapped in quantum wells and quantum boxes. A major challenge of nanotechnology is to learn whether the only limits are the sizes of atoms and molecules, or whether the limits are higher.

Nanotechnology tools and processes may be subdivided into two classes, (1) top-down: those achieving miniaturization by starting from macroscopic objects, i.e. conventional lithographic processes used by the microelectronics industry and (2) bottom-up: those which, at least conceptually, build upward from single atoms and molecules to larger scale nanostructures.

The Competitors and Stakes

Nanotechnology has been identified as a major emerging technology in Europe, Japan, and the USSR. Japan has launched a national thrust in nanotechnology called the ERATO Program. The ERATO Program currently consists of nine projects ranging from the Yoshida Nano-Mechanisms Project to the Molecular Dynamics Assembly Project. Total funding for the ERATO Program is estimated to be between $10 M and $20 M per year; beginning in 1981 and extending at least through 1991. In addition, Japan has organized a major industry-university consortium under the auspices of the Research and Development Association for Future Electronic Devices, and this Association is being funded by the Japanese Ministry of International Trade and Industry at a budget of $65 M over an eight year period beginning in 1986. The National Initiative on Nanotechnology (NION) has been started in the U.K. as part of the larger LINK program to encourage cooperative efforts between government, industry, and universities. Funding for the U.K. NION program is about $15 M over four years from the government to be matched by industrial funds. A major effort in molecular electronics is also underway at the Nanoelectronics Research Centre at the University of Glasgow. In W. Germany, programs in various aspects of nanotechnology have been initiated at the Max Planck Institutes and at the Fraunhofer Institutes. In the USSR, the Soviet Academy of Sciences has also started a major research effort in molecular computing.

By the year 2000, the electronics and related industries will almost certainly be completely redefined in terms of structure, participants, and in the way that products are designed, manufactured, and marketed. The journal, Electronics, forecast that by 1996, without major efforts by the US to reverse current trends, Texas Instruments, Inc. will be the only U.S. merchant IC maker in the world's top ten IC manufacturers. There is a possibility that IBM will become a merchant IC maker in the next decade. Nanotechnology is one of the key enabling technologies to maintain and strengthen the US position in the extremely important product areas of micromachines, advanced robotics, exotic materials, and information technology.

The importance of a nation's industries ability to achieve the next generation of miniaturization is vividly illustrated by the slaughter of U.S. memory chip manufacturers in 1986. This occurred as a result of the announcement by Japanese chip manufacturers that they had developed the technology for miniaturization that enabled them to manufacture 128 thousand bit chips and subsequently to sell them at the same prices that U.S. manufacturers could sell 64 thousand bit chips. Within months, every U.S. Manufacturer of memory chips lost their market and thousands of Americans lost their jobs. Even the IBM Corporation was forced to buy the Japanese memory chips and install them in their personal computers.

The Role of NIST in the Technology

The proposed program will enable NIST, working collaboratively with U.S. industry and other governmental and university laboratories, to develop a generic science-and-technology base for nanotechnology. Because of the extreme dimensional precision and accuracies demanded by nanotechnology, NIST will develop and make available to domestic industries appropriate instrumentation for generating and measuring nanometer displacements, highly accurate nanometer length artifacts, and important data on materials and processes. With this strong base in manufacturing and measurement and a long standing expertise in intelligent machines, NIST will also contribute to the development of new devices and circuit architectures.

Science Base and R & D

Under this program, NIST will conduct interdisciplinary research and development on the manufacturing processes necessary for the preparation of nanometer-scale devices; the microscopies needed to "see" at the atomic and molecular scales; the instruments and mechanisms needed to generate, measure, and control the position of probes on this nanometer scale; and the tools and processes to provide the capability to pick-up, move, and deposit atoms and molecules. The range of disciplines and supporting technologies includes metrology, precision engineering, electrical engineering, surface science, physics, chemistry, materials science, and biophysics/chemistry.

Generic Technology and Production

The proposed NIST program will develop the technology base necessary to develop available and new enabling technologies, to develop important standards and dimensional artifacts, and to facilitate their development and adoption by domestic industry as a basis for improving U.S. competitiveness in the world market based on nanotechnology. NIST will also develop — in collaboration with industry and university counterparts — non-product-specific technologies that are necessary for enabling U.S. industry to rapidly develop forefront capabilities in nanotechnology.

For nanotechnology, major enabling technologies for forming nanostructures include: Langmuir-Blodgett and other molecular monolayer thin film techniques; electron, ion, and photon — optical and X-ray — beams and lithographies; molecular beam epitaxy, scanning tunneling microscopy, and direct synthesis of molecular and other nanostructures. Generating, controlling, and measuring the position of probes on the nanometer scale will require the continued development of ultra-high resolution optical interferometry, new tribological systems that permit wear rates to be in the range of fractions of a nanometer per kilometer of travel, and refined forms of current systems for generating nanometer displacements. All of these technologies are currently being explored by NIST with the Molecular Measuring Machine (M^3) and Molecular Manipulation projects. The M^3 project goal is to develop a planar coordinate measuring machine capable of positioning and measuring to atomic scale accuracies over an area of 25 square centimeters. The Molecular Manipulation project is directed at exploration of methods and processes to controllably add and remove material on the atomic scale to highly perfect surfaces in order to form useful devices on the nanometer scale.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This is an internal report produced by the managers and staff of the Center for Manufacturing Engineering for planning purposes only. It represents our current best thinking about emerging technologies in manufacturing engineering, the impact these technologies will have on our programs, and the directions our programs will go if sufficient resources are available. The emerging technologies discussed are those that we believe will require increased support and leadership from CME in coming years.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

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