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NATIONAL
ADVANCED
MANUFACTURING
TESTBED

TOWARD 21ST CENTURY INFORMATION-BASED MANUFACTURING

United States
Department of Commerce
Technology Administration
National Institute of
Standards and Technology

NIST SPECIAL PUBLICATION 913

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ABSTRACT

The National Advanced Manufacturing Testbed (NAMT), recently begun by the National Institute of Standards and Technology (NIST), is designed to help U.S. industry speed the transition to 21st century manufacturing capabilities. Through the NAMT—a distributed testbed built on a state-of-the-art, high-speed computing and communications infrastructure—scientists and engineers from industry, NIST, academia, and government agencies are working together to solve measurement and standards issues that impede companies and industries from making the most of their information technology. Initiated by NIST's Manufacturing Engineering Laboratory, this unique "collaboratory" is both an Information Age workbench and showcase for demonstrating how machines, software, and people can be networked together, efficiently and effectively, to improve productivity and foster innovation at all levels of a manufacturing enterprise. This report describes the vision, goals, and initial projects of the NAMT program. It also describes ways for outside organizations to participate in the program.

KEY WORDS

collaboratory, communications infrastructure; distributed enterprises; high-speed computing; information technology; manufacturing; National Advanced Manufacturing Testbed; simulation; standards

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SEIZING THE INFORMATION TECHNOLOGY ADVANTAGE

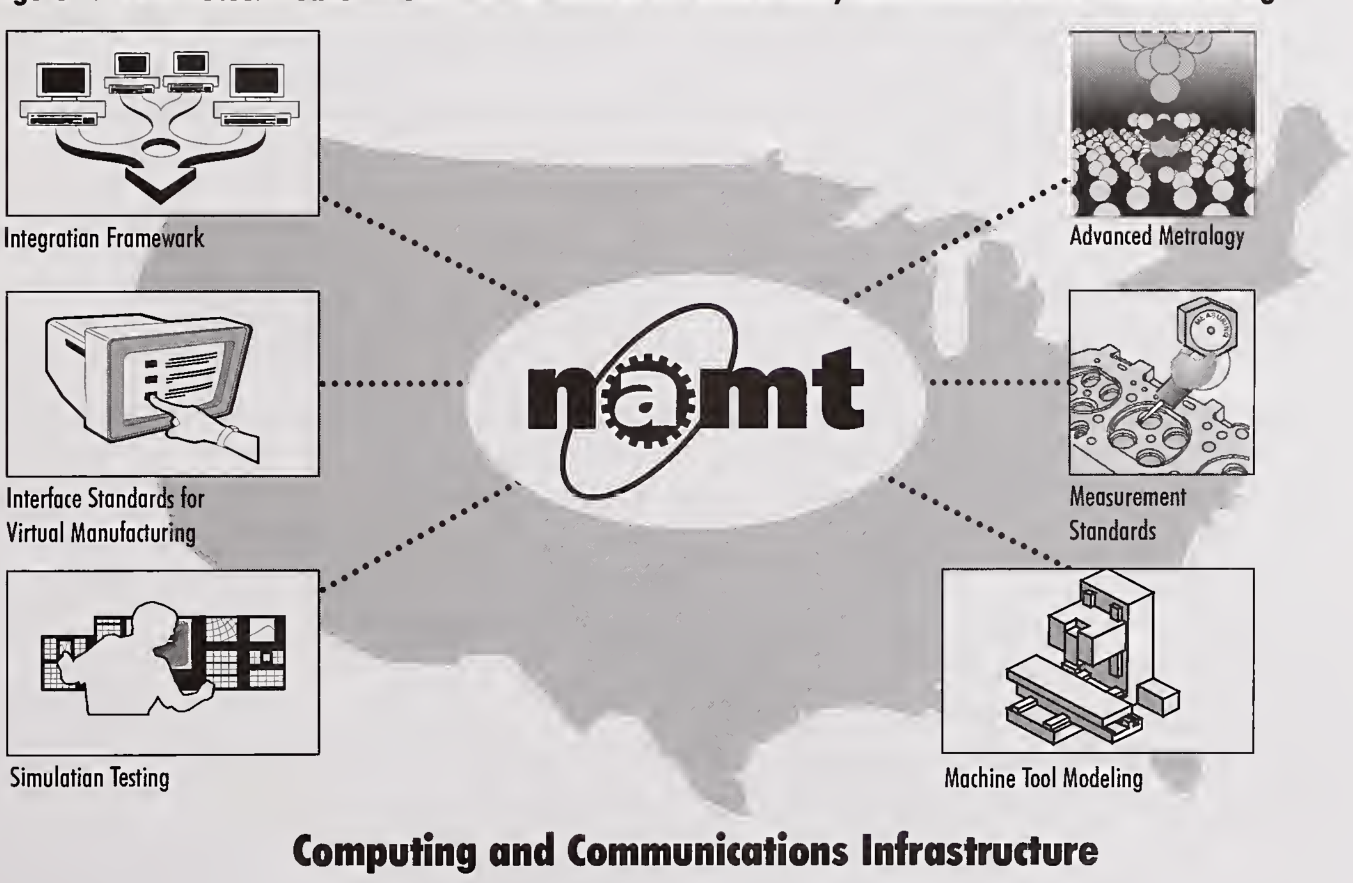
From interchangeable parts toward interchangeable factories, from mass production toward mass customization, and from trial-and-error experimentation toward modeling and simulation, the transition to information-based manufacturing is under way. As the timely capture, sharing, analysis, and management of information grow in importance as value adding elements of manufacturing, companies are changing the way they organize and operate.

The National Advanced Manufacturing Testbed (NAMT), recently begun by the National Institute of Standards and Technology (NIST), is designed to help U.S. industry speed the transition to 21st century manufacturing capabilities. Through the NAMT—a distributed testbed built on a state-of-the-art, high-speed computing and communications infrastructure—scientists and engineers from industry, NIST, academia, and government agencies are working together to solve measurement and standards issues that impede companies and industries from making the most of their information technology. (See fig. 1.) Initiated by NIST's Manufacturing Engineering Laboratory (MEL), this unique "collaboratory"[1] is both an Information Age workbench and showcase for demonstrating how machines, software, and people can be networked together, efficiently and effectively, to improve productivity and foster innovation at all levels of a manufacturing enterprise.

For U.S. manufacturing organizations, the NAMT offers a tremendous opportunity to pool resources and capabilities, to share risks, and, most important, to efficiently build the technical underpinnings of an advanced information infrastructure. Such a foundation of communication and computing facilities, services, and standards will yield sectorwide benefits, while enabling individual companies to leverage their own information technology investments.

Altogether, the nation's manufacturers now spend more than $16 billion on information technology—software, hardware, and data collection—and total

Figure 1. NAMT Focus: Measurements and Standards for Distributed, Information-Based Manufacturing



THE AMRF: SUCCESSFUL PARTNERING

The NAMT is the next-generation successor to NIST's highly successful Automated Manufacturing Research Facility (AMRF), which was partly sponsored by the U.S. Navy Manufacturing Technology Program. In this NIST-based laboratory, collaborators from NIST, U.S. companies, universities, and other government agencies developed the means to integrate individual machine tools, workstations, and production functions into a smoothly operating whole.

AMRF researchers developed automated manufacturing control techniques that were among the most advanced in the world, yet used off-the-shelf components. They demonstrated the power, flexibility, and practicality of standard interfaces that enabled equipment from many different suppliers to operate together. These researchers also established the basis for software-based, accuracy-enhancement methods that integrated measurement into the manufacturing process. This accomplishment led to increased precision, quality, and productivity in U.S. manufacturing, as well as a competitive market advantage for equipment makers that adopted the technology.

Work at the AMRF led to about 30 new or emerging voluntary standards, 20 patented inventions, and 25 process and product applications. More important, the AMRF demonstrated a path for computer integrated manufacturing at the factory level. It helped catalyze the transition to today's manufacturing model. Nearly 100 guest researchers worked at the AMRF, making significant contributions to its legacy of technical accomplishments.

The AMRF closed in 1995 as NIST and an advisory group of industry and government representatives were completing plans for the NAMT. Though this new distributed research facility is geared to meeting a more advanced set of technical needs, it will benefit from the AMRF's demonstrated successes in fostering productive collaboration.

Box 1

annual expenditures are increasing at nearly double-digit rates.[2] These investments, however, may not yield full value. Targeted performance improvements and competitive advantages may not reach their full potential. The reason: the means to flexibly integrate processes, systems, and companies on geographic scales are lacking.

Without interface standards, communication protocols, and other key infrastructural technologies, efforts to integrate new equipment and processes into existing operations and systems will continue to consume inordinately large amounts of money, time, and staff. Beyond the internal operations of individual firms, opportunities to leverage the capabilities of partners and to develop closer relationships with customers may go unrealized.

The NAMT is an important vehicle for building information-based manufacturing's equivalents of roads, bridges, interchanges, and even mass transit rails—the means to transform information technology and its applications into highly productive inter- and intraorganizational linkages. In this distributed, multi-project testbed, which links people, facilities, and resources at sites around the country, collaborators from NIST, companies, universities, and government laboratories have begun the critical task of developing, demonstrating, testing, and refining prototype standards for achieving integration and interoperability within and across systems, factories, and enterprises.

Effective collaboration is key to accomplishing the testbed's ambitious technical goals. Successful partnering is a long-standing tradition at NIST and its Manufacturing Engineering Laboratory. The NAMT's predecessor is the Automated Manufacturing Research Facility, launched in the 1980's to focus on standards and measurement issues in factory-floor automation. (See box 1.) This research factory of the future fostered a new, productive style of collaboration that delivered useful technical results to U.S. industry.

Times have changed, and the NAMT is responding to new challenges that confront the U.S. manufacturing sector. To respond effectively, it is pioneering new modes of collaboration. By enabling long-distance collaboration, the NAMT serves as a platform for fostering industry consensus on sorely needed information technology standards. Together, through the capabilities and resources accessible through the NAMT, manufacturing organizations can join forces to eliminate shared technical obstacles to next-generation manufacturing capabilities. NIST invites all organizations concerned about the future of U.S. manufacturing to learn more about the NAMT and to participate in efforts designed to accomplish the industry-driven objectives of the testbed.

NEW CHALLENGES, NEW OPPORTUNITIES

Advances in the performance of computing, communication, and networking technologies are delivering opportunities for tremendous improvements in manufacturing processes and practices. These technological advances are occurring alongside other equally significant changes that are reshaping the world of manufacturing and business competition: Markets are fragmenting, customer demands are becoming more specialized, and product life cycles are shrinking. The importance of suppliers is growing, accounting for an increasing share of the value-added content of finished products. World-class manufacturing capabilities are sprouting in newly industrializing countries around the globe, while established, export-minded companies are building production facilities close to growing foreign markets.

These and other fluid conditions present major challenges and major opportunities. They also are a prescription for action, as summarized by a representative of the nation's aerospace manufacturing sector:

We must determine a new way of doing business. In order to succeed in global competition, we need to find a way to accommodate low-rate production . . . affordably. We need to be flexible so that we can build the latest technology and developments into our processes and into our factories to reduce costs. . . . We need to shorten the product development cycle, reduce risks through application of all elements of virtual prototyping, modeling, and simulation with integral cost analyses, and, finally, provide world class quality . . . at the lowest cost. [3]

Figure 2: What's Next in Manufacturing?

"Information Technology is the Key Enabler"

The Future. In all sectors, manufacturers are seeking to identify and develop the fundamental attributes of a successful 21st century enterprise. A general conceptual consensus on the hallmarks of future manufacturing competitiveness has emerged, as illustrated in figure 2. All require capabilities enabled by effective applications of information technology. Especially critical capabilities include operational and product flexibility, cost-effective product-customization, modularity of equipment and processes, knowledge-based operational and strategic decision making, and integration within and among enterprises.

The Present. Today, companies are not fully realizing these capabilities. Examples in box 2 illustrate some of the difficulties and obstacles that manufacturers—from the smallest to the largest—are confronting. All are symptomatic of major voids in the infrastructure needed to support manufacturing applications of information technology.

Without an underpinning foundation of communication protocols, interfaces, and other industry-adopted standards, even companies that are investing large sums in information technology will eventually reach a dead-end. "The use of advanced technologies within our company," an automotive company executive has noted, "will have only a marginal impact on our competitiveness if our supply base does not have access to the same technologies."[4]

Today, this access is largely restricted because of the lack of interoperability among competing vendors' systems and subsystems. As pointed out recently by a panel of manufacturing experts, better standards are fundamental to building the technological acumen and capabilities of suppliers and original equipment manufacturers alike, while reducing the costly risk of premature technological obsolescence. (See the recommended response in box 2.)

WHY THE NAMT

COSTS OF INCOMPATIBILITY AND LACK OF INTEROPERABILITY . . .

- A 1993 study found that the higher the level of computerization, the less flexible a plant's ability to make a large range of products or to change swiftly between products. A prime impediment: Difficulty in adapting software to accommodate unanticipated changes.[1]
- To avoid disruption and minimize retraining costs, a U.S. manufacturer recently decided to refurbish 100 machine tools with controllers identical to the decade-old versions that the company was replacing, rather than introduce more advanced and more capable controllers with a different "look and feel."
- In 1995, U.S. industry is estimated to have spent about $1.6 billion for contractor- provided control system integration services.[2]
- Suppliers may have 10 or more different types of CAD systems to satisfy specifications peculiar to the equipment of each of their major customers.
- Within companies, databases with incompatible formats have evolved to serve particular production and management needs, even though many require much the same information. The consequences are redundant inputting, data management nightmares, and lack of up-to-date information to support decision making.
- Modernization efforts by capital-pinched smaller manufacturers are impeded by the lack of interoperability among off-the-shelf hardware and software, limiting their choices and flexibility and increasing the risk of premature obsolescence of their technology.

[1] Maruca, Regina Fazio, "Manufacturing Flexibility—Practice Makes Perfect." Harvard Business Review, p. 10, Nov.-Dec. 1993.

[2] "Control System Integrators Mark Major Growth." Control Engineering, pp. 36-37, June 1996.

. . . AND A RECOMMENDED RESPONSE

"Research is needed to develop better manufacturing architecture, standards, and interfaces, including research to develop standard equipment control architectures and generic functionality within the architectures, to support general manufacturing information standards, and to lower the cost of more open, less proprietary architectures. Especially desirable would be architectures whose standards accommodate some upgrade capability, so that technology vendors could worry less about premature freezing of technology and the locking out of potential competitive advantages, while customers could worry less about intrinsic obsolescence."

—Committee to Study Information Technology and Manufacturing, National Research Council, Information Technology for Manufacturing: A Research Agenda, p. 122, National Academy Press, Washington, D. C., 1995

Box 2

THE NAMT: OPENING THE WAY TO ADVANCED CAPABILITIES

The vision for 21st-century manufacturing presumes that interconnecting manufacturing applications will be as simple as connecting household appliances—one need only know how to run the application . . . and manage the interface . . . The ease of interconnection and interoperation extends from devices found on the factory floor to applications connecting the factory to the product design facility to applications connecting an enterprise to its suppliers and customers . . . [5]

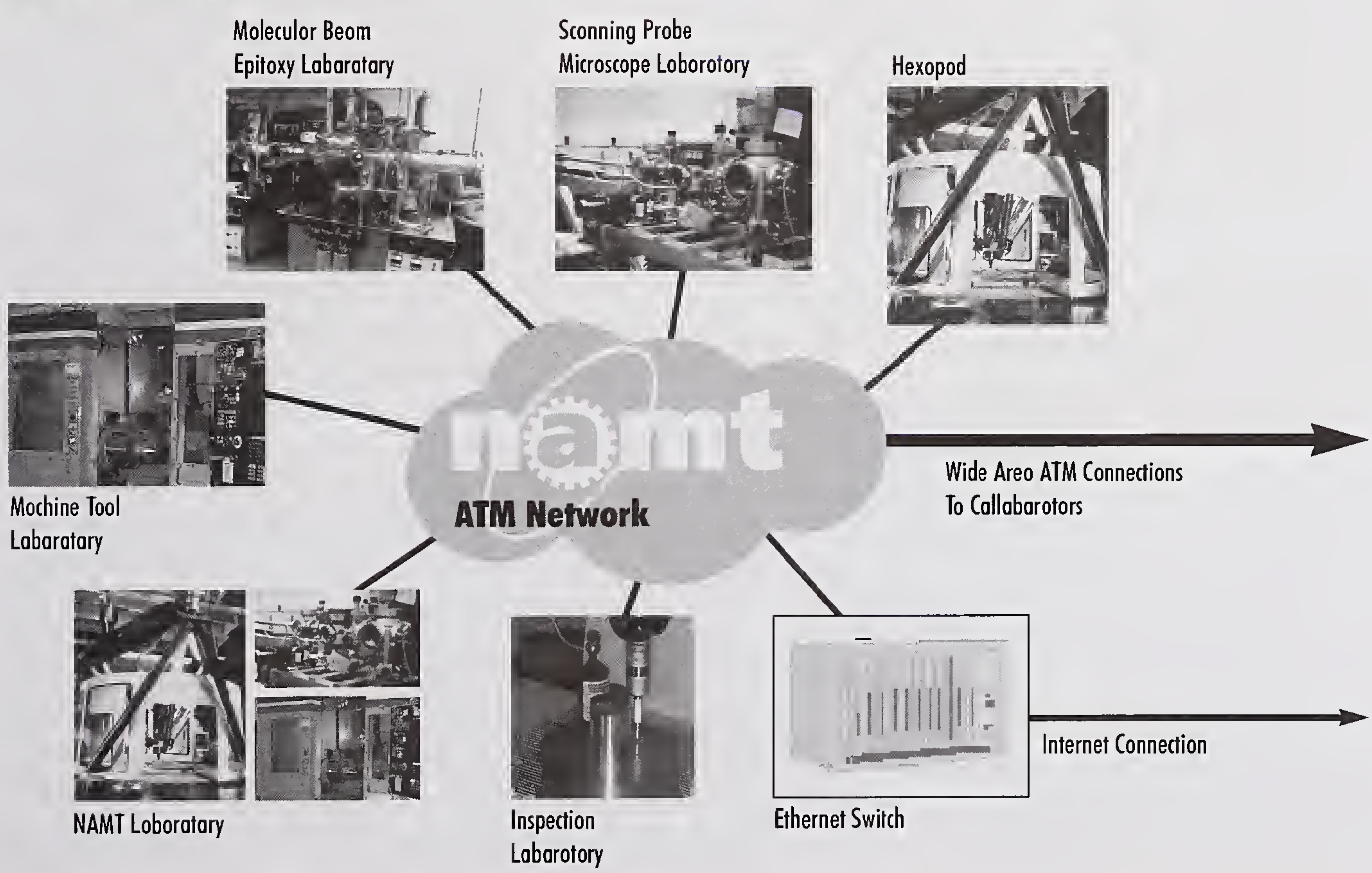
Through an evolving set of advanced manufacturing R&D projects and by means of a state-of-the-art computing and communications infrastructure, the NAMT provides a vehicle for realizing this vision of 21st-century manufacturing. Planned and developed with the encouragement and participation of industry and government executives, the NAMT enables cross-disciplinary, collaborative research on standards-related and metrology issues.

The overall goals of the NAMT are to:

- Enable and accelerate development of standards for facilitating the interoperability of manufacturing systems and the rapid insertion of new technologies into these integrated systems.
- Facilitate on-site and remote collaborations and to enable access to geographically distributed resources.
- Serve as a research testbed for developing and evaluating information-based manufacturing capabilities and applications.

Results of NAMT research and demonstrations, such as measurement and process-control techniques, interfaces, information models, and architectures, speed the development and validation of infrastructural technologies necessary for information-based manufacturing. Because these results will be obtained in a research environment akin to that envisioned for next-generation manufacturing operations, they will be in a form that can be readily refined and adapted to the

Figure 3. NAMT High-Speed Network



needs of particular companies and industries. Prototype standards can be advanced as starting points for committees and working groups of national and international standards bodies.

The Infrastructure. Like state-of-the-art manufacturing enterprises of the future, the testbed has geographically distributed partners and emphasizes virtual technology. That is, the equipment, expertise, and capabilities of NAMT partners are electronically connected through the testbed's common infrastructure. Moreover, collections of resources and personnel can be easily configured—and reconfigured—in response to changing research needs and objectives. The virtual technology elements of the testbed will support research on applications of simulation and modeling methods that are essential to rapid prototyping and fast fabrication, among a host of other key capabilities. Work at the NAMT will be devoted not only to developing and validating models and simulations of individual processes, but also to ensuring the integrity and accuracy of computerized representations of the performance of entire manufacturing systems.

The NAMT infrastructure supports real-time interactions among collaborators and real-time access to hardware and software. (See fig. 3.) It integrates voice, video, and data on the same network to create a cohesive collaborative environment. Today, in contrast, organizations use separate networks dedicated to particular uses, such as telephone networks for voice communication, packet-switching networks for data transmission, and closed circuit television for videoconferencing.

Information technology resources available to NAMT partners are:

- **Physical communications components,** such as networking gateways, routers, and networking software, that provide collaborators with access to equipment, documents, databases, project information, test data, and testing suites.
- **Commercial and experimental software applications,** such as design, engineering, and simulation packages that are remotely accessible, as well as advanced capabilities, including teleoperating physical devices.
- **Multimedia communications,** such as videoconferencing, groupware, and e-mail exploders, to facilitate effective collaboration among remotely located partners, as well as security and safety mechanisms.
- **Advanced machine tools and research equipment** that might otherwise be unavailable to collaborators.
- **Vast and varied technical expertise** that is immediately accessible through the national network.

The NAMT as Collaboratory. The value of information technology lies largely in connections, in links between applications, resources, and facilities. This is why NAMT projects emphasize developing the means to quickly assemble—and, as competitive circumstances dictate, reassemble—these linkages. This also is why collaboration is so essential. Standards—the means to achieving interoperability, modularity, and reconfigurability—cannot be developed in isolation. Developing robust, technically sound standards requires the participation and expertise of original equipment makers, parts suppliers, machine-tool makers, and software and hardware vendors, as well as contributions from manufacturing researchers in government and universities.

Through the NAMT's computing and communications infrastructure, geographically dispersed collections of people, resources, and capabilities can be configured to accomplish the research tasks of NAMT projects. Without leaving their home facility, collaborators have access, for example, to NIST's hexapod machine tool or its Next Generation Inspection System Laboratory, as well as to highly specialized and highly capitalized equipment housed at the sites of other testbed partners in industry, academia or at other sites. They can also share data and software tools, teleoperate remotely located physical devices, and work cooperatively, using multimedia capabilities that enable direct interaction among electronically linked colleagues.

NAMT-facilitated linkages enable partners to develop the technical basis for integration and interoperability standards required for distributed and virtual manufacturing capabilities. Just as important, the NAMT is used to demonstrate and test prototype standards, necessary for achieving broad industry acceptance and for paving the way to subsequent adoption and application.

Individual NAMT Projects: Part of the Whole. For NIST and its partners, the NAMT provides a highly leveraged opportunity to address technical issues across the breadth of manufacturing and, at the same time, to respond to process-specific problems and needs. All current and future NAMT research will contribute to an open set of standards, interfaces, architecture specifications, and other infrastructural elements that enable varied sets and subsets of manufacturing systems to work together.

Individual projects, however, often focus on specific process technologies and capabilities, such as intelligent machine control, machine characterization

AN EXAMPLE OF NAMT-ENABLED COLLABORATION

Distributed manufacturing, intelligent control, supply-chain optimization, these and many of the other advanced capabilities expected to drive manufacturing competitiveness in the 21st century will require an unprecedented degree of interoperability, on unprecedented scales. One NAMT project, undertaken with consortia, voluntary standards groups, and other organizations, aims to develop and demonstrate an enterprise framework, a common environment for integrating software applications and sharing information across activities, functions, and organizations.

Such a software infrastructure, with standardized modular elements, would permit individual companies and groups of companies to rapidly develop - and, just as rapidly, revamp - products, processes, and systems.

Consortia contributing to the development of interoperability specifications and protocols include the:

- National Industrial Information Infrastructure Protocols Consortium, an 18-organization effort focusing on protocols and other standards to enable the creation and operation of virtual enterprises;
- Semotech, a consortia of semiconductor manufacturers and equipment makers that has developed an object-oriented integration framework for "chip" fabrication; and
- Technologies Enabling Agile Manufacturing program, a government-industry program that is led by the Department of Energy and is devoting significant effort to modeling manufacturing process and developing software applications to support those processes.

Other participants include the Object Management Group, a consortium with more than 600 members, mostly software vendors, developers, and end users. OMG has developed a software architecture to further the development and application of object-oriented software. Researchers contributing to the NAMT Framework Project also interact with relevant bodies of the International Organization for Standardization, or ISO. Examples are the ISO committee that is coordinating the development of STEP, the Standard for the Exchange of Product Model Data, and the NIST-led ISO working group on enterprise modeling.

The project builds on standards that already exist or are under development, although gaps in these efforts will require NAMT collaborators to develop prototype specifications that will be needed to integrate applications and share information across organizations. The NAMT framework will evolve, permitting researchers to analyze alternative standards and prototypes in various manufacturing operations.

In the project's initial phase, the focus will be on developing the framework to support automated inspection of mechanical parts. Succeeding efforts will expand the focus to production control and simulation, planning and design applications, and framework-to-framework interoperability, which will enable supply-chain integration. (Additional detail on the initial set of NAMT projects can be found in the appendices.)

Box 3

and simulation, high-speed machining, and advanced inspection and measurement techniques. An integral requirement for all these efforts is that they yield solutions that are modular—integratable elements of larger systems. The integratability of process-specific results may foster additional advances and advantages, as well as unanticipated applications in other processes.

Initial Portfolio. In 1996, the NAMT's information infrastructure was operational, and four projects were inaugurated. All projects were formally reviewed by teams of technical experts and managers from manufacturing companies, universities, and government agencies. Each involves partners from outside organizations, which are devoting personnel and resources
to the collaborations. The goals of initial NAMT projects are described briefly below. (More detailed descriptions of the projects and testbed infrastructure can be found in the appendices.)

- **Machine-Tool Performance Models and Machine Data Repository:** Using standardized data formats, develop predictive machine-tool and inspection-system models that enable accurate simulation of performance in specific applications. A standardized approach to structuring and representing detailed performance information is a key element of virtual manufacturing environments.
- **Characterization, Remote Access, and Simulation of Hexapod Machines:** Measure and extend the capabilities of still-experimental, parallel-actuated machine tools. Collaborators are benchmarking and then, through applications of information technology, extending the capabilities of this promising, new machine-tool technology.
- **Nanomanufacturing of Atom-Based Standards:** Using emerging distributed and virtual manufacturing capabilities, fabricate and disseminate prototype dimensional standards with features derived from the geometries of atomic lattices. Work will lead to important measurement reference artifacts for the microelectronics and nanotechnology industries.
- **Framework for Discrete Parts Manufacturing:** Provide industry with tests and methods for analyzing and validating standards, pre-standard specifications, and other middleware technologies developed by consortia and other organizations to promote interoperability of manufacturing systems across enterprises.

Although the projects differ greatly in specific technical objectives, each will ultimately lead to advances in the application of information technology to manufacturing. Each also draws on and integrates the distributed expertise, capabilities, and resources of NIST and a network of outside organizations, as exemplified in box 3.

LEVERAGING THE NAMT: HOW TO PARTICIPATE

An innovation in research collaboration, the NAMT will speed development of a critically needed information infrastructure for U.S. manufacturing. Cooperation, collaboration, and consensus are essential to building this key requirement for future manufacturing competitiveness. From the discrete parts manufacturing sector, the initial industrial focus of NAMT efforts, collaborators include large original equipment manufacturers, parts suppliers, makers of machine tools and other process-related hardware, and software vendors, as well as consortia.

These industrial collaborators have joined with the NIST's Manufacturing Engineering Laboratory and groups from others of the Institute's major laboratories. Government participants also include several Department of Energy national laboratories and the Department of Defense. NAMT activities are linked to complementary manufacturing technology research programs housed in other agencies. In addition, university researchers contribute to all ongoing testbed projects, and academic representatives, like their counterparts from industry and government, participate in the planning and review of NAMT projects.

Collaborating organizations benefit through:

- Access to advanced technical expertise and manufacturing research capabilities at NIST and the facilities of other networked NAMT partners.
- Participation in, and experience gained from, the development, demonstration, and validation of prototype standards and new process applications.
- Direct interaction with NIST and access to the worldwide measurement and standards communities.

In addition, the NAMT is a vehicle for overcoming organizational and competitive complexities that can impede development of standards and their wide-scale adoption. Collective experience gained while conducting collaborative experiments and demonstrations helps to foster confidence in protocols, interfaces, and other NAMT-enabled infrastructural technologies that will deliver their greatest benefit when applied on industrywide scales.

The NAMT accommodates different levels of participation. Means to enter into formal arrangements include Cooperative Research and Development Agreements, Guest Research Agreements, the NIST Industry Fellows Program, and contracts. Intellectual property concerns, if any, and the expected outcome of joint efforts usually dictate the type of arrangement. Interested companies, universities, and other organizations are encouraged to participate in NAMT workshops and conferences.

Getting Started. Interested companies and other prospective partners are encouraged to review descriptions of the NAMT's initial portfolio of projects and to capitalize on the capabilities of the testbed's infrastructure and distributed resources. All projects are evaluated on the basis of criteria that measure how well the work will contribute to meeting industry-identified needs for standards and measurements that will enable information-based manufacturing; how well the work leverages the work of existing programs at NIST and other organizations in government, industry, and academia; the importance of the work to prospective collaborators; and the ultimate anticipated impact on U.S. industry.

Whom to Call. Participation in the NAMT is a strategic opportunity worth exploring. The unique collaborative capabilities presented by this state-of-the-art collaboratory for research on information-based manufacturing enable organizations to capitalize on technological changes and help to ensure their future competitiveness of U.S. industry. By working together through the NAMT, the nation's manufacturing and research organizations can efficiently build the infrastructure that will put U.S. industry in a position to seize the advantage in the global marketplace of
the 21st century.

To become a participant in the National Advanced Manufacturing Testbed, call or send an e-mail message to:

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Fax: (301) 926-8730
or visit the NAMT home page at:
http://www.nist.gov/mel/namt

END NOTES

1. National Research Council, Committee on a National Collaboratory: Establishing the User-Developer Partnership, *National Collaboratories: Applying Information Technology for Scientific Research*, National Academy Press, Washington, D.C., 1993.
2. Parker, Kevin, "Manufacturing apps rule," *Manufacturing Systems*, September 1996.
3. J.M. Sinnett, McDonnell Douglas Aerospace, "Aerospace Sector Needs and Issues." In *Proceedings of the Second Annual Manufacturing Technology Conference: Toward a Common Agenda*, April 18-20, 1995. NIST Special Publication 886.
4. Frank J. Ewasyshyn, Chrysler Corp., "Needs and Opportunities: A Chrysler Perspective." In *Proceedings of the Second Annual Manufacturing Technology Conference: Toward a Common Agenda*, April 18-20, 1995. NIST Special Publication 886.
5. National Research Council, Committee to Study Information Technology and Manufacturing *Information Technology for Manufacturing: A Research Agenda*, p. 122, National Academy Press, Washington, D.C., 1995.

APPENDIX A: COMPUTING AND COMMUNICATIONS INFRASTRUCTURE

Need: As manufacturing enterprises become more distributed, robust computing and communications infrastructures that integrate voice, video, and data services are needed to productively link geographically separated facilities and functions. Today, different types of special-purpose networks serve as links. Telephone networks carry voice traffic. Closed-circuit TV networks carry video. Packet switching networks, like the Internet, carry computer data traffic. In the future, high-speed networks will be used to integrate voice, video, and data traffic over a single physical network and to bring these multimedia services to the desktop. The National Advanced Manufacturing Testbed has built an integrated multimedia infrastructure to examine and exploit the technology's capabilities to the benefit of U.S. manufacturing.

Goal: To provide a distributed, multimedia, computing, and communications infrastructure, as required by NAMT projects. The infrastructure includes: 1) state-of-the-art computing capabilities; 2) a leading-edge, high-speed communications network to connect the NAMT project sites (internal and external); and 3) a multipurpose laboratory at NIST that will be used by NIST researchers and collaborators to work on NAMT projects.

Approach: The high-speed NAMT network was constructed using Asynchronous Transfer Mode (ATM). This new network technology combines the best features of circuit-switched networks (like the telephone network) and packet-switched networks (like the Internet). ATM was built from the ground up to carry voice, video, and data traffic. Unlike traditional Local Area Networks (LANs) that share the available bandwidth among all the attached users, ATM dedicates bandwidth to each user. This allows users to send voice and video communications without traffic delays caused by heavy use of the network by others.

The ATM network currently spans four buildings at NIST. It connects ATM-attached workstations and servers, Ethernet switches (used to provide connectivity to less demanding workstations), and audio/video encoders and decoders that enable TV-quality audio and video across the network. In the future, the ATM network will be expanded to reach external collaborators via ATDnet, a Washington-area ATM network. This extension will test the effectiveness of ATM in wide-area networks applications.

NAMT workstations include a variety of Sun, SGI, and PC computers that provide access to a wide variety of manufacturing applications and provide desktop video-conferencing capabilities across the network.

The NAMT Laboratory is a multipurpose computer room that can be used for research, meetings, training, demonstrations, and other uses. It contains a 230 cm (90 inches) video wall that can display data and images resident on NAMT lab computers as well as real-time audio and video from any of the NAMT project sites. The video wall serves as the window into the NAMT and is used to demonstrate the integrated, distributed manufacturing environment that has been put into place.

Benefits: The effectiveness of high-speed, integrated, multimedia computing and communications infrastructures, as applied to distributed manufacturing enterprises, will be demonstrated.

Progress: FY 1996 accomplishments include: 1) construction of a fiberoptic ATM backbone network that connects four buildings on the NIST campus; 2) construction of the NAMT laboratory; 3) installation and configuration of new NAMT workstations (Suns, SGIs and PCS); 4) installation and configuration of real-time audio and video hardware located at several NAMT project sites at NIST.

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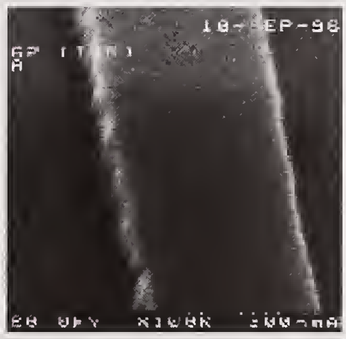
APPENDIX B: NANOMANUFACTURING OF ATOM-BASED DIMENSIONAL STANDARDS

Need: Two major trends in industry are driving forces for this project. First, the ever decreasing dimensions and tolerances that characterize the products of the semiconductor and data-storage industries pose serious challenges to measurement and quality control capabilities. According to industry projections, the critical dimensions of microelectronic devices will decrease to about 100 nm within a decade, requiring dimensional standards with uncertainties near 1 nm and a degree of geometric perfection near to that of an ideal atomic lattice. The second major industry trend—resulting, in large part, from the first—is the demand for ever cleaner, more precisely controlled manufacturing environments. Currently, these trends are being manifested in the move from clean rooms to mini-environments to clean machines and in the use of standard mechanical interface, or SMIF, pods to transfer materials between the manufacturing tools.

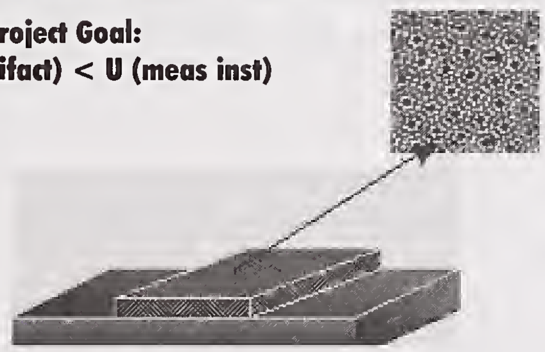


SEM image of typical linewidth standard now: U(artifact) > U(meas inst)

In response, NIST is undertaking development of atom-based dimensional standards—those with feature sizes and geometries derived directly from that of the atomic lattice. Some such standards will likely need to be fabricated, transported, and used at different sites, spending their lives under vacuum. At the same time, growing numbers of microelectronic devices are being produced at different manufacturing sites. Expensive equipment is specialized to perform different steps of the overall manufacturing process, including research and development, design, fabrication, inspection, processing, or repair. Often, these steps are dependent upon sophisticated computer modeling, communications and control.

Goal: To support the development and deployment of the technology of: distributed fabrication and use of nanometer-scale dimensional artifacts; computer modeling and simulation of mechanical systems and components, including artifact transport systems, such as a "vacuum suitcase"; remote teleoperation of scanned probe microscopes; and linking by advanced computers and communications for high-speed video, voice, and data transmission among collaborating institutions in industry, government, and academia.

One Project Goal: U (artifact) < U (meas inst)



Approach: This project aims to: 1) demonstrate the feasibility of fabricating calibration standards with nanometer-scale dimensions and feature sizes and shapes determined by crystal lattice spacings and geometries achieved through controlled natural processes, such as lattice dislocations; 2) develop a standardized-interface, portable-artifact transport system to enable the physical transport, under vacuum, of wafers and other substrates undergoing processing in high-vacuum systems in clean-room facilities at different geographical locations; and 3) demonstrate remote diagnostic operation of scanned probe microscopy systems, using standard data representations and controller interfaces.

Benefits: This project will lead to: 1) next-generation calibration standards of accuracies needed to meet industry's projected needs; 2) interface standards for atom-based artifact transport systems; and 3) interface standards for remote teleoperation of SPMs.

Progress: FY 1996 accomplishments include: 1) initial technical planning and design of the project; 2) external review of the project technical plan by representatives of industry and academia; and 3) an initial demonstration of the virtual and distributed aspects of project activities involving simulations; telerobotic operations; and voice, data, and image communications among different geographical locations. Plans for FY97 include: manual fabrication of a first prototype of one type of atom-based artifact; development of a formal project definition document based on the results of the external review; design and fabrication of a functionally specified vacuum suitcase; and test of the motion control and interface for teleoperation of a prototype SEM or SPM.

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APPENDIX C: CHARACTERIZATION, REMOTE ACCESS, AND SIMULATION OF HEXAPOD MACHINES

Need: Rapid production of quality contoured parts requires machine tools that combine speed, accuracy, stiffness, and multi-axis versatility. In addition, manufacturers look for machine-tool features, such as ease of installation and movability, that enable plants to be reconfigured to meet changing market demands or to realize operational improvements. A new class of parallel-actuated machine tools based on the Stewart platform mechanism presents new possibilities for meeting these needs.

However, much remains to be learned about the characteristics of these "hexapod" machine tools before they will see widespread application in production. Industry workshops have highlighted the need for:

- In-depth understanding of the characteristics of these new machines.
- Standard test methods and measurement procedures to evaluate performance.
- A reservoir of application experience to draw from.
- Modeling and simulation tools, for development of applications and test methods.
- Remote access capabilities, to make it easier for external collaborators to interact and participate in the work being done.
- Examination of controller and integration issues.

Goal: To develop methods to characterize and extend the limits of performance of a new class of Stewart platform-based machine tools—in terms of accuracy, productivity, and versatility—through the development and implementation of virtual and distributed manufacturing technologies.

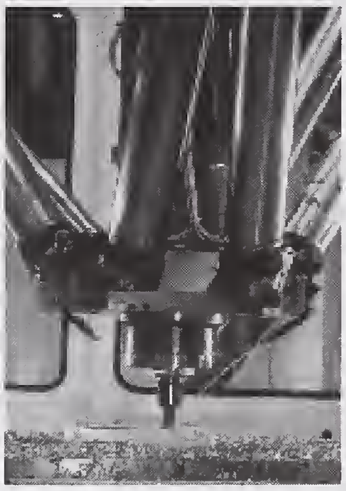
Approach: To address the needs discussed above, the NAMT Hexapod Project team and its external partners will perform work in the three areas: characterization, remote access, and simulation. Work at NIST will be performed on the octahedral hexapod machine, installed at the agency's Gaithersburg, MD, site. Models, measurement techniques, and other project results will be developed in a generic form, enabling application to other Stewart platform machines. NIST researchers are participating in a recently formed Hexapod Users Group, and plan to interact with this group to coordinate research activities and share results.

In developing performance evaluation techniques, the approach will be to use the ANSI/ASME B5. 54-1992 Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers and ISO 230 as starting points for characterization. As necessary, modifications to the test procedures will be proposed to ensure that appropriate evaluation methods are available for hexapod machines. Performance enhancements, such as improved calibration and feedback metrology techniques, will also be pursued as understanding of basic machine behavior increases.

For remote interaction, high-speed, dedicated communications links, such as ATM, will be used as one means of providing real-time transfer of audio/video and sensor data to researchers at remote sites. Another (most likely, Internet-based) version of these capabilities will also be developed to provide interactive capabilities at lower cost, but with some compromise in performance.

To examine controller and integration issues, the project team will install an open-architecture controller on the hexapod. Application programming interfaces (APIs) and software developed under the

NIST Enhanced Machine Controller (EMC) project will serve as the initial foundation for this part of the project. From the validation of machine motions to detailed investigation of the errors and structural dynamics of the hexapod, a comprehensive set of modeling and simulation tools is needed to reduce the risks and increase the effectiveness of hexapod research efforts. These simulation capabilities will be developed in an incremental fashion, gradually adding to the fidelity and detail of the modeled behavior.



The practicality of making some of these animation and simulation tools accessible remotely will be explored as a means for providing potential new partners with a convenient way to obtain some initial experience with the hexapod machines.

Benefits: Potential benefits of hexapod machines cited in the trade literature include increased stiffness, higher speed and acceleration due to reduced moving mass, and reduced production and installation costs as a result of machine symmetry and its self-contained structure.

The research to be performed in this project will result in:

- New performance evaluation techniques and standards to allow objective comparisons of different types of these new machines.
- Performance enhancements, such as calibration techniques and feedback metrology systems for higher accuracy.
- Opportunities for machine tool users to gain first-hand experience with this new technology.
- Networked sensor and control information for remote experimentation, interaction and integration.
- Program validation, workspace analysis, part placement, and other simulation tools for faster application development.

Progress: FY96 accomplishments include: 1) developed initial ball-bar based kinematic calibration technique; 2) with the Department of Energy, demonstrated distributed manufacturing capability with hexapod simulation; 3) developed hexapod modeling and simulation capabilities using Pro/Engineer and TeleGrip; 4) performed initial development of World Wide Web interface to TeleGrip animation; 5) began implementation of EMC for test strut; 6) built laser metrology system mount and performed experiments with laser metrology system on test strut; 7) with the University of Maryland, developed first-generation workspace analysis and part placement tools, and static stiffness model; 8) held internal and external NAMT project reviews and participated in Hexapod Users Group meeting; 9) performed static stiffness testing of machine with Pratt & Whitney; 10) developed machining applications for demonstrations; 11) developed error visualization capability using "ghost image" in TeleGrip; 12) examined the thermal behavior of the Hexapod; and 13) performed static and dynamic structural analysis of 2D parallel mechanism similar to hexapod.

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APPENDIX D: FRAMEWORK FOR DISCRETE PARTS MANUFACTURING

Need: Driven to improve competitive performance, U.S. manufacturers invest billions of dollars each year in information technology. A substantial portion of this investment is allocated for creating and integrating applications software. Chief among these integrated applications are manufacturing execution systems (MES), product data management (PDM) systems, database management systems (DBMS), computer aided manufacturing (CAM), and factory control systems, as well as planning and scheduling systems. Many of these applications and most of the software used in their integration are non-standard, one-of-a-kind creations. Now, manufacturers are trying to replace their in-house software systems with standards-based, off-the-shelf products. They want to reduce their outlay of capital and human resources on systems development, integration, and maintenance in order to focus on core manufacturing competencies and to improve operational flexibility.

Industry requires the capability to rapidly integrate "best-in-class" applications, improve interoperability, defer obsolescence, increase system stability, and integrate widely distributed manufacturing operations. Information technology standards provide these benefits, while reducing technical and financial risks. However, no single standard exists that will satisfy all of the system interoperability needs of manufacturing organizations. Consequently, development and adoption of suites of information technology standards are key elements in the competitive strategies of many U.S. manufacturing organizations. Validation testing of candidate standards is a critical technical ingredient of these strategies. Manufacturers use validation testing to determine profiles of standards. Information technology vendors use test results to garner marketplace confidence and to reduce technical and risks associated with the adoption of new technologies embedded into modern, complex manufacturing systems.

Goal: The Framework Project will provide industry with tests and methods for analyzing and validating emerging manufacturing information standards and technologies. Work will be focused on information models for manufacturing, software application interface definitions, object-oriented class hierarchies, data access protocols, scheduling and control strategies, integration mechanisms, and communication architectures.

Approach: The Framework Project will perform analyses and validation testing of standards, pre-standard specifications, and other so-called middleware technologies developed by industry consortia.
The approach taken in this project is to implement a distributed manufacturing software system based on the combined use of emerging standards and technologies. This test system will consist of MES, PDM systems, DBMS, CAM systems, and factory control systems, as well as planning and scheduling systems. Testing will be conducted against a manufacturing scenario representative of the defense, aerospace, and automobile industries and entailing the design, production, and inspection of discrete metal parts. The results of the implementation and testing form the basis for documented reviews of the specifications. These reviews address the internal consistency of each specification as well as the technical relationships between the specifications. These reviews are used as input to ongoing development within the various
consortia and they are used in the formal consensus building process within standards organizations.
The Framework Project test system will be extended based on industry need and in cooperation with collaborating researchers and

Benefits: Expected benefits include: 1) Test-generated information will be used in standards profiles, aiding strategic standards management; 2) Validation of emerging standards and technologies is expected to reduce the standards development cycle-time; 3) Standards-based information technology is expected to increase product quality, decrease time-to-market, reduce product development costs, and increase the efficiency of manufacturing operations; and 4) The adoption and use of standards will reduce costs for manufacturing-system end users and will allow system providers to profit from economies of scale.

Progress: Recent milestones and accomplishments include: 1) review of the Framework Project plan at a workshop of industry leaders; 2) implementation at NIST of a distributed manufacturing software system based on emerging technologies and standards under development by U.S. industry consortia; 3) validation testing and analysis of the system's elements against a manufacturing scenario and production data; 4) publication of draft reports on the preliminary analyses and validation tests of the technologies implemented in the test system; 5) convened a workshop of industry leaders to determine the need for and recommended scope of a new model of manufacturing inspection information; 6) development of a preliminary activity model for inspection information; 7) participation in industry-led focus groups; and 8) participation in standards efforts underway in the International Organization for Standardization (ISO) and the Object Management Group.

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APPENDIX E: MACHINE TOOL PERFORMANCE MODELS AND MACHINE DATA REPOSITORY

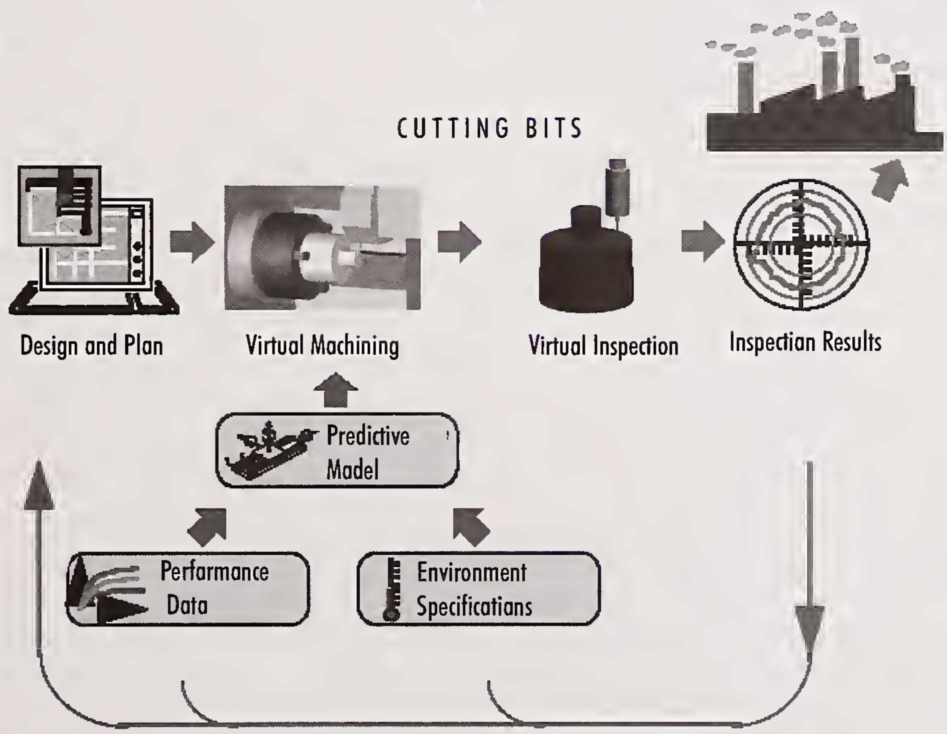
Need: To reduce costs and respond rapidly to changing customer needs, large companies are relying increasingly on a network of suppliers and outsourcing a significant percentage of their manufacturing needs. This type of geographically and organizationally distributed manufacturing requires better communication and improved coordination and utilization of internal and external manufacturing resources by all the participants.

Because of the need to shorten design and production cycles, designers and production engineers must collaborate closely to determine the optimum use of resources required to turn designs into real products, without extensive prototyping. Prototyping is usually an iterative process, taking considerable time and effort before the actual production can begin. Creating a virtual manufacturing environment to simulate the complete manufacturing cycle and carry out this iterative process in the virtual domain presents a unique opportunity for industry to reduce time for new product introduction.

Goal: Develop tools that enable design and manufacturing engineers to predict machine tool performance and to ensure that parts can be machined to specification with a minimum of prototyping. These tools include data structures and low order machine models that represent actual machine behavior; mathematical representation of actual part geometry, including dimension and form errors; virtual machining algorithms; virtual inspection algorithms; standardized data formats; and remotely accessible machine data repositories.

Approach: This project aims to replace actual machining and inspection of parts during prototyping with virtual machining and virtual inspection modules incorporated into a CAD/CAM system. The virtual machining module will simulate the movement of the cutting tool when making a part. In this simulation, the effects of error motions, predicted from machine-tool characterization data, will be reflected in the tool path. Virtual machining will result in an electronic approximation of the part that can be inspected by the virtual inspection module. The virtual inspection module will determine the uncertainties associated

Virtual Prototyping



with the selected inspection plans and equipment. These uncertainties will be checked against the specified design tolerances of the part. This virtual environment will make it possible to optimize the manufacturing process by trying different machines and making changes to the process plans or part designs.

One major challenge will be the development of a data structure for electronic representation of machine performance and error characteristics. Such a data structure will enable different manufacturing entities to effectively share information on available manufacturing equipment. The types of information necessary for this purpose include error characteristics of machine components, descriptions of machine structure, axis designations, error notations, and sign conventions. Based upon the proposed data structure, a data repository for storing machine performance information will be created. This repository may be populated by major manufacturers and their suppliers as well as machine tool vendors. Algorithms will be developed to access performance data from this repository and to apply the data in predictive machine models.

Benefits: The results of this project will contribute to a variety of important benefits, including: 1) optimum and speedy allocation of in-house and/or supplier manufacturing resources, which will significantly shorten time for new product introductions; 2) improved quantitative information exchange between design engineers, manufacturing engineers, and process planners; and 3) optimization and quality assurance of existing manufacturing processes.

Progress: Recent activities and accomplishments include: 1) technical planning; 2) external industry review of the project's technical plan; and 3) an initial demonstration of concepts of virtual machining. For this demonstration several machine tool models were developed and incorporated into a commercial software package for machine structural analysis. The virtual parts created by this virtual machining software were compared against the parts made and inspected on real machines. The concept of predicting and representing a machined part in a computer environment was demonstrated.

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