The Automated Manufacturing Research Facility

Over the years, NBS/NIST has built various experimental facilities to support its assigned functions of custody, maintenance, and development of national measurement standards, and provision of the means and methods for making measurements consistent with those standards. Such facilities include a nuclear reactor, a cold neutron source, a linear accelerator, a fire research facility, and dead weight force generators. It was in this tradition that the Automated Manufacturing Research Facility (AMRF) was established. The AMRF was designed to anticipate the measurement and standards needs of the discrete parts manufacturing industry in the 1990s and beyond. This 1982 paper [1] describes the history of NBS efforts to meet the measurement needs of U.S. manufacturing industries, beginning with artifact standards and calibrations during the first half of the century, and evolving to measurement protocols based on laser interferometer calibrations of coordinate measuring machines by the 1960's. The paper also describes early work in control system architectures that provided the basis for the AMRF research in interface standards for information exchange within computer-based manufacturing systems.

During the 1970s, two significant trends had become clear:

1) Computers were playing an increasingly important role in manufacturing.
2) Measurements were increasingly integrated into the closed-loop control of machines and processes.

The first trend meant that interface standards would be needed to facilitate exchange of information between computer systems. The second meant that in-process measurement technology would be needed for real-time feedback control. To address interface standards, the AMRF focused on developing information exchange requirements and a reference model architecture to understand the interactions between components of computer-based manufacturing systems. To address the in-process measurement issues, the AMRF focused on methods for instrumenting machines and integrating measurements into the machining process. Inspection would be performed on-line while parts were being manufactured, in addition to, or instead of, off-line after the fact.

Prior to the 1970s, most measurements of manufactured products were based on artifact standards such as gage blocks, thread gages, and line scales. NBS supported industry by providing calibrations that tied these artifacts to national and international standards of length. Industry compared their manufactured products with these artifact standards by statistical quality control methods. Products were typically inspected off-line after the manufacturing process had been completed.

During the 1960s and 1970s, the concept of Measurement Assurance Programs began to emphasize the system aspects of measurement. Coordinate measuring machines (CMMs) were introduced into the inspection process and closed loop feedback methods became part of metrology management. CMMs increased the reliability with which comparison with artifacts could be accomplished and improved productivity by reducing the time required to make measurements. Of course, coordinate measuring machines were themselves subject to errors that were consequently introduced into the measurement process. However, these errors were in large part systematic. Simpson and Hocken observed that a typical coordinate measuring machine was an order of magnitude more repeatable than it was accurate [2]. This suggested that if the systematic errors were modeled and stored in a computer, then the computer could compensate for those errors. During the 1970s, NBS work in calibration and computer correction of coordinate measuring machine errors made a significant contribution to measurement technology for manufacturing [3]. The concept of in-process measurement and computer based error compensation also provided the conceptual foundation for the AMRF approach to measurement technology.

Also during the 1970s, NBS work in robotics and neural networks began to address issues of intelligent control. The goal of this research was to bridge the gap between high level concepts of artificial intelligence (such as perception, knowledge representation, and planning) and low level concepts of feedback control. The approach was to develop a system architecture that could support the decomposition of high level manufacturing tasks into lower level subtasks in a succession of hierarchical steps until, at the bottom, subtask commands could be input directly to servo control loops. At each level of the hierarchy, signals from sensors were processed to extract the information needed for real-time control decisions at that level. This sensory-interactive goal-directed control architecture became known as the Real-time Control System (RCS.) RCS was intended to be a reference model architecture with a canonical form that could be used to define standard interfaces between modular components [4].

Concurrent with the development of RCS, work was begun on interface standards to facilitate exchange of information between various commercial Computer-Aided Design (CAD) systems. Under the technical leadership of Roger Nagel and Bradford Smith, the Initial Graphics Exchange Specification (IGES), which is described elsewhere in this volume, became a national standard. IGES was an immediate success. Within a few years, virtually all manufacturers of CAD systems provided IGES interfaces for their systems [5]. Together, the RCS control architecture and the IGES data exchange standard provided the conceptual foundation for the AMRF work on interface standards [6]. Fig. 1 is a diagram of the AMRF control system architecture.

AMRF consisted of six workstations integrated into a group technology cell. Orders were input through cell control [7]. (The shop control shown in Figure 1 was never implemented.) There were three machining workstations, a cleaning and deburring workstation, an inspection workstation, and a material handling workstation. Part designs and process plans were developed interactively by human programmers off-line. A management information system provided information about the status of the factory [8, 9, 10].

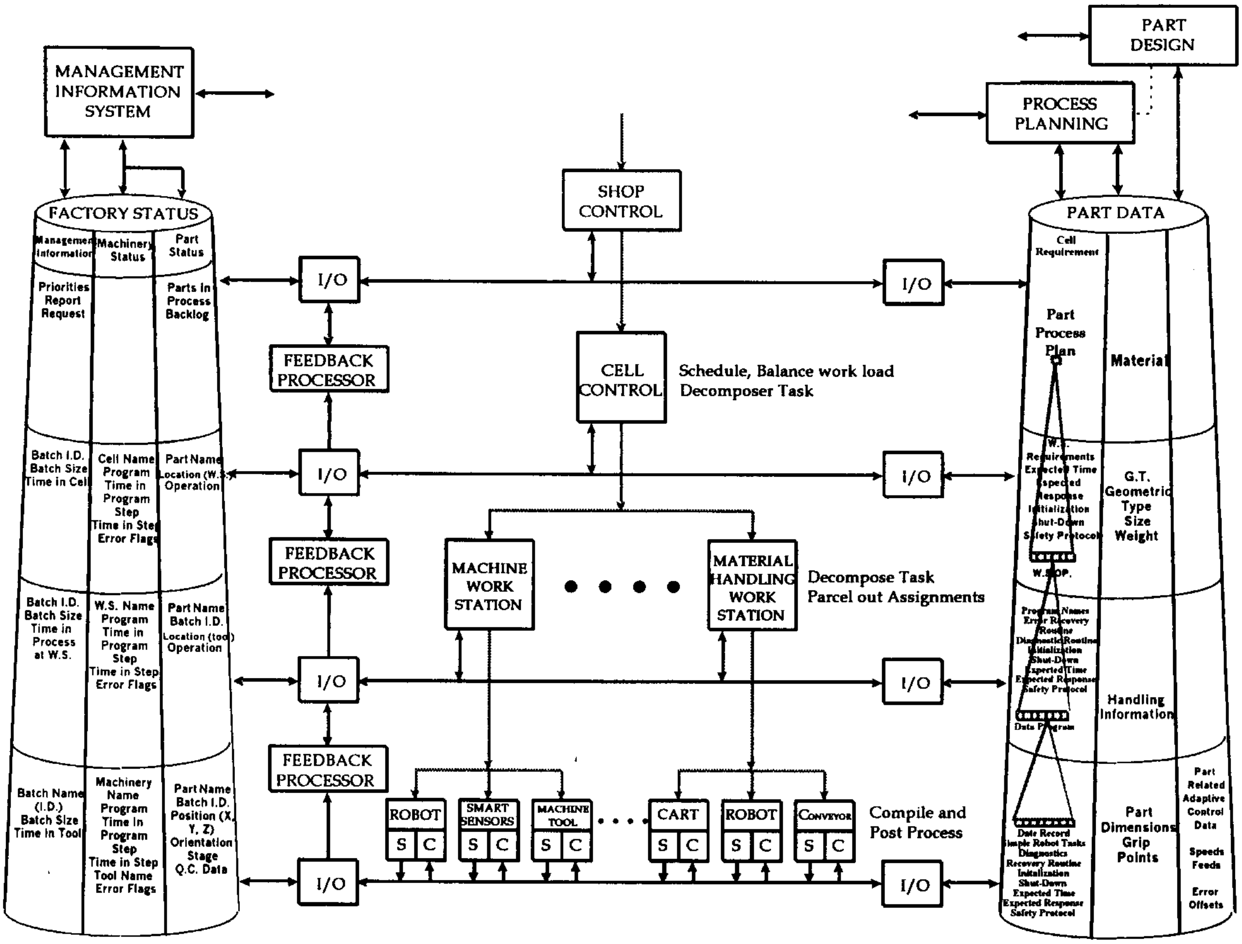

Fig. 1. Architecture for the NBS Automated Manufacturing Research Facility (AMRF). On the right is a hierarchical database containing process plans and control programs that define how to manufacture parts. On the left is a hierarchical database containing information about the state of the parts and machines in the AMRF. In the middle are the controllers that compute plans, sequence commands, measure results, and compute actions to compensate for errors between plans and results. The arrows represent a communications system that moves information throughout the architecture [1].

The six workstations included the:

1) *Horizontal Machining Workstation*

The major subsystems of the HWS included a horizontal spindle milling machine, a robot, and a set of buffers. The machine tool was equipped with a tool changer, a pallet shuttle, and an automatic vise for holding parts. The buffers were used to store tools, parts, and fixtures. They were serviced by an automatic wire-guided vehicle. All of the HWS subsystems were coordinated by the RCS workstation controller. The robot, machine tool, buffer, and automatic fixture were also equipped with RCS control systems that enabled them to accept commands from the workstation controller. The robot had vision and tactile sensors that enabled it to sense the position and orientation of parts and tools, and to load and unload them to and from the machine tool. The robot vision system used structured light to detect the three-dimensional position and orientation of parts in a buffer tray and to measure their size and shape. Tactile sensing enabled the robot to "feel" a part being grasped and to sense when it had been properly inserted into a fixture for machining. The HWS robot had the dexterity to remove a part from the fixture, turn it over, and re-insert it for machining the opposite side. It could also load tools into the machine's tool carousel. The robot was equipped with a quick-change wrist so that different grippers for different shaped parts and tools could be handled. The RCS controllers, each typically consisting of several computers on a bus, were integrated through an experimental AMRF network and database [11, 12, 13].

2) *Vertical Machining Workstation (VWS)*

The VWS consisted of a vertical spindle milling machine, a robot, and a menu-driven programming system whereby parts could be designed and machined automatically from a feature-based design. A simple two-and-a-half dimensional part could be designed and machined within an hour, allowing half an hour for design input. Workstation activity was divided into design, process planning, data execution, and physical execution stages. To make VWS operation safe and accurate, extensive error prevention and verification procedures were incorporated in the data preparation stages. Automatic verification included design editor dialogues, design enhancement, design verification, process plan verification, work-piece verification, and part model checking. Interactive verification included design drawing, work-piece model drawing, and tool path drawing [14, 15, 16].

3) *Turning Workstation (TWS)*

The major components of the TWS included a turning lathe, a robot to load and unload parts and tools, and buffers to store parts, tools, and fixtures. The TWS was equipped with position sensors, accelerometers, thermal sensors, and laser interferometers. A special purpose gripper was developed with a micro-manipulator that enabled the robot to perform high precision insertions required for loading parts in the lathe collet. The Turning Workstation addressed problems associated with untended turning operations. These included automatic tool changing, work piece loading and unloading, and tool setting. The TWS enhanced the accuracy of the turning lathe by real-time software error compensation. Thermally induced errors were predicted based on calibration and measurement of machine position, direction of motion, and temperature profile. During machining, predicted errors were compensated by machine servo algorithms. Software error correction improved overall machine accuracy by about an order of magnitude [17].

4) *Inspection Workstation (IWS)*

The IWS contained a four-axis coordinate measuring machine, a robot, and a variety of inspection probes for measuring part dimensions and surface finish. Parts were delivered to the IWS by automatic wire-guided vehicles. They were loaded onto the coordinate measuring machine by the robot and inspected. Measurements were compared against dimensions and tolerances in the part design data. Statistics were kept on dimensions within tolerance so that machining operations could be adjusted to maintain quality. Dimensions outside of tolerance were flagged. Surface finish data was also collected [18].

5) *Cleaning and Deburring Workstation (CDWS)*

The CDWS consisted of two robots, a set of buffing wheels, a set of deburring tools, a part holding fixture, a washer/dryer, and a storage buffer. Both robots had integrated force/torque sensors that enabled them to sense forces and modify their motions so as to correct for small errors and tool wear. One robot performed buffing operations. The second had a tool changer that enabled it to use a variety of abrasive brushes and deburring tools. The CDWS controller had a computer-aided programming system that enabled an operator to select tool orientation, force, and speed parameters for each deburring operation. The system then automatically generated a control program for the tool path and manipulation operations necessary to load each part into a fixture and perform the specified set of deburring operations [19, 20].

6) *Material Handling Workstation (MHWS)*

The MHWS workstation consisted of a part and tool storage carousel, a storage and retrieval system, an automatic wire-guided delivery cart, and a workstation controller. The storage carousel had sufficient capacity for one week of operation. The MHWS controller responded to requests by the other workstations for delivery and pickup of parts and tools. The MHWS planned a route and dispatched its delivery cart to the appropriate workstation at the proper time [21].

The AMRF also included three infrastructure support projects. These were the Integrated Manufacturing Data Administration System (IMDAS) [22], the AMRF Network Communications system [23, 24], and the Hierarchical Control System Emulator [25]. IMDAS provided the database management services necessary to store and retrieve the control programs that specify how to manufacture each part, and the part data files that specify geometry and tolerances for each part feature. The Network Communications system provided the data transmission services required to support the AMRF control system architecture. The control system emulator enabled programmers to develop software in a virtual environment. Control programs could be tested and debugged on emulated machines that were indistinguishable from real machines to the control system software.

During its lifetime, several thousands of people visited the AMRF and explored with its scientists and engineers issues of concern to their companies. Examples of the comments received from industrial visitors are:

> *"The AMRF provides a good architecture for factory automation which we are using in our internal factory automation program. We are picking up a lot of concepts such as feedback loops, world modeling, and planning. We are developing a generic cell based on the AMRF architecture."* [26].
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> Mr. Bob Solberg, Chairman,
> Factory Automation Council
> Boeing Computer Services,
> Boeing Company

> *In 1984 I joined the Aircraft Engine Group of General Electric as the Manager of Automation for a flexible turning center to be built in Lynn, MA. The NBS/AMRF hierarchical control structure was one of the models we used in designing the computerized control system for that plant. More than this, the AMRF provided us with a reference, something we could check ourselves against. Some of the things being done at the AMRF are profound in my view. For example, AMRF researchers introduced error maps to facilitate the use of computer-based temperature correction to upgrade the precision of a milling machine."* [26].
>
> Mr. Robert D. French, Manager
> T700/CT7 Engine Programs
> General Electric Company,
> Aircraft Engine Business Group

Over the years, technology from the AMRF was transferred into industrial production. As a follow-on to the AMRF Turning Workstation, NBS researchers designed and built a flexible manufacturing workstation for the Mare Island Naval Shipyard. The Mare Island workstation was developed to manufacture a family of 40 different pipe connectors designed to inhibit the transmission of sound in nuclear submarines. The workstation was equipped with an NC lathe, live tooling, a robot, an automated storage and retrieval system, and an AMRF style control system. It was designed to work unattended. Previous manual techniques required 17 hours to produce a typical part. The new workstation could manufacture the same part in as little as 20 minutes.

Lessons learned from the Mare Island workstation were put into practice in another version of the AMRF Turning Workstation built for the Portsmouth Naval Shipyard. The Portsmouth workstation was designed to manufacture and inspect class-1 fasteners (i.e., critical bolts, studs, and cap screws) for nuclear submarines. These fasteners were made of k-monel, a very strong, corrosive-resistant metal that is difficult to machine. Personnel from the Portsmouth shipyard worked closely with NIST scientists to make the technology transfer successful [27].

The RCS control system architecture developed for the AMRF was adapted for use in several areas outside of manufacturing. Under DARPA funding, RCS was adapted for control of multiple autonomous undersea vehicles. DARPA also supported the adaptation of RCS for command and control systems aboard next generation nuclear submarines. The U.S. Bureau of Mines adopted RCS as an architecture standard for automated mining operations. RCS was adopted by the U.S. Postal System for control of a stamp distribution center and a general mail facility. NASA adopted a version of RCS called NASREM (NASA/NBS Reference Model) as a controller for the Space Station telerobotic servicer. NASREM was also adopted by the European Space Agency as a model for their robotics program. For the past ten years, RCS has been used by the Army for their research program in Unmanned Ground Vehicles [28]. The Air Force Next Generation Controller program and the industry led Open Modular Architecture Control (OMAC) consortium have been influenced by the AMRF control architecture.

Among the long term results of the AMRF was the influence it had on the transformation of NBS to NIST. According to a report by the National Academy of Sciences [29]:

“The AMRF served as a platform to develop needed technology for flexible, integrated, and automated manufacturing of discrete parts. Originally conceived as a testbed for integration of advanced automation, it successfully proved a number of concepts and eliminated less promising ones. It has played a significant role in the identification and development of emerging technologies in manufacturing. It has had considerable influence on various private efforts throughout the nation. It was also the catalyst for the legislative process that resulted in the Technology Competitiveness Act” (the section of the Omnibus Trade Act of 1988 which reauthorized NBS and NIST.)”

Besides changing the name from NBS to NIST, the Trade Act added two new programs to the NIST responsibilities: The Advanced Technology Program (ATP), and the Manufacturing Technology Centers (MTC) which became the Manufacturing Extension Partnership (MEP.) The MTC program was originally conceived as a mechanism for transferring manufacturing technology from the AMRF to industry.

The AMRF was jointly funded by NBS and the Navy Manufacturing Technology Program. The program managers for the Navy were Jack McInnis and. Steve Linder. The number of people involved in the AMRF is much too large to give proper credit to everyone by name or to cite every related publication. The bibliography gives a sampling of the more significant publications.

Prepared by James S. Albus.

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