The Automated Manufacturing Research Facility of the National Bureau of Standards

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Abstract

A major facility for manufacturing research is being established at the National Bureau of Standards (NBS). The facility is designed to provide extreme flexibility and to be capable of emulating a wide variety of manufacturing cells typical of a small machine job shop. The control architecture adopted is hierarchical in nature and highly modular. The facility will be used for research on interface standards and metrology in an automated environment.

Keywords: Automated Machining, Hierarchical Control, Manufacturing Research, Research Facility.

The Congressional Act* setting up the National Bureau of Standards charges the Bureau with:

1. The custody, maintenance, and development of the national standards of measurement, and the provision of means and methods for making measurements consistent with those standards.
2. Cooperation with other government agencies and with private organizations in the establishment of standard practices, incorporated in codes and specifications.

To perform these functions, the Bureau has, over the years, installed numerous experimental facilities, including a nuclear research reactor, a linear accelerator, and dead weight force generators with a capacity of 4.4 meganewtons. The National Bureau of Standards has recently embarked on the design, procurement, and installation of a new Automated Manufacturing Research Facility (AMRF) to support its measurement and standards responsibilities in the decades of the 1980s and 1990s. When completed in 1986, this facility will be capable of full-scale emulation of the flexible machining cells in the automated factory of the future.

Purpose of the AMRF

The Automated Manufacturing Research Facility will reside in the Center for Manufacturing Engineering which was founded to supply to the mechanical manufacturing sector the services described in the enabling legislation and to carry on a research program to develop "means and methods" for making the measurements that will be needed by this sector in the future. The Center currently provides a wide range of calibration services for mechanical artifact standards such as gage blocks, thread gages, and line scales as shown in *Figure 1*.

These artifact standards, many of which were developed by NBS in the first three decades of this century, are idealized models of the products to

*Act of 22 July 1950, 64 Stat. 371 (Public Law 619, 81 Congress)—An Act To amend section 2 of the Act of March 3, 1901 (31 Stat. 1449), to provide basic authority for the performance of certain functions and activities of the Department of Commerce, and for other purposes.

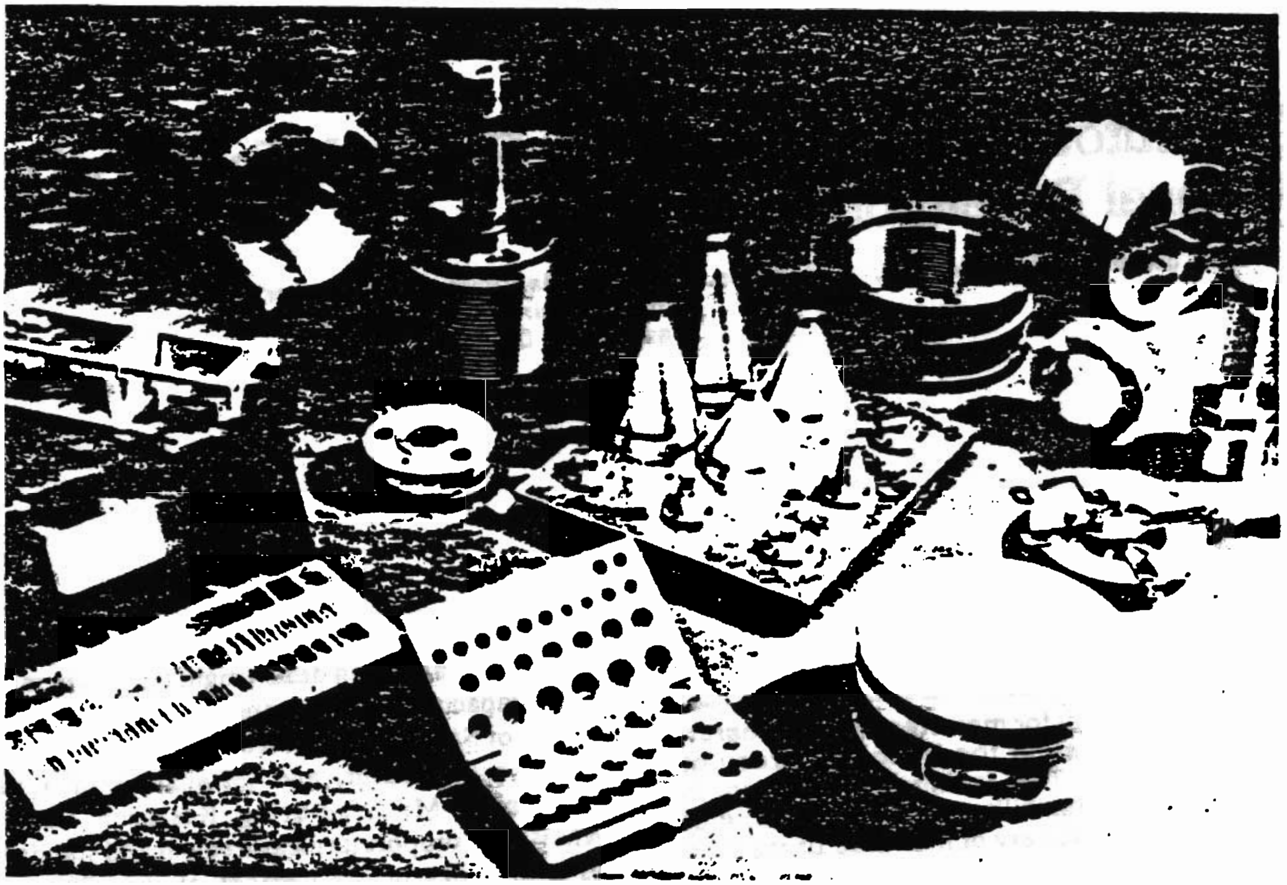

Figure 1
Artifact Standards Typical of those now Calibrated by NBS

which they are compared. The comparisons (calibrations) are organized according to statistical quality control methods developed during and immediately after World War II. Artifacts currently are the basis for the National Measurement System which provides nation-wide dimensional compatibility by a chain of comparisons back to National Standards. The system has remained virtually unchanged since the 1940s, except for the introduction in the 1960s and '70s of the concepts of Measurement Assurance Programs (MAP)[1], which emphasize the system aspects of measurement and introduced the concepts of closed loop feedback into metrology management.

Manufacturing technology, however, has not remained unchanged. The introduction of numerically controlled machines, group technology concepts, and the first steps toward Flexible Manufacturing Systems (FMS) in the 1960s called attention to the labor intensive nature, high skill requirement, and time consumption of classic metrology.

The first effort of NBS to meet the up-coming challenge was in 1968 when a research program was mounted to investigate the possiblility of automating surface plate metrology by the use of the then new computer controlled coordinate measuring machines (CMM). A decade of work realized a measurement system based on such machines where the "product-like" artifact standards of the past were replaced with measurement protocols based on laser interferometer techniques for characterizing the measuring system (coordinate measuring machine) itself. Transfer standards were developed that permitted such machine or process characterization to be economically realized on machines of lesser but known precision[2]. The three-dimensional ball plate on the table of the CMM in *Figure 2* is one of the latest of such standards. These new measurement

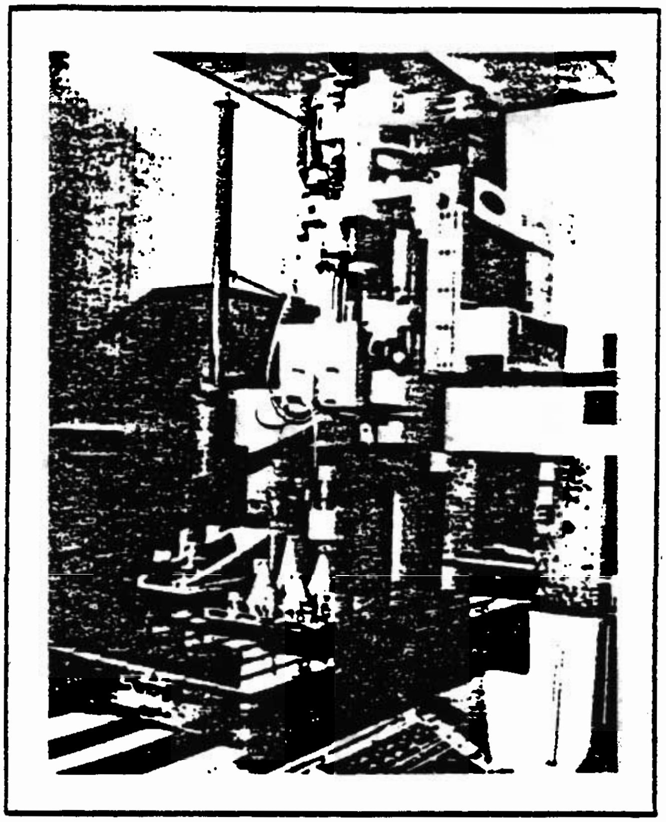

Figure 2
Coordinate Measuring Machine, with He-Ne Laser Scales under Computer Control, Calibrating a 3-Dimensional Ball Plate used to Characterize Similar Machines at other Locations

methods are rapidly becoming the norm for certain part families. These families are medium to large in size and complex-prismatic in nature, and hence similar to the output of the first and second generation FMS.

Even before this work was completed, it became obvious that there were many part families that were ill-suited to measurement by CMM. Small parts, turned parts, and very simple parts are all either very difficult or uneconomic to measure in this manner. Moreover, the rapid development of FMS, with the ability to reduce inventory by shorter runs, casts doubt on the continuing usefulness of any QC system which depends on statistical sampling. Along with others, NBS became convinced that the QC system of the future would increasingly depend on characterization of the process, monitoring of the machine parameters, and adaptive control rather than measurement of part parameters after the process, or a step in the process, was complete. Such a development will require NBS to provide the "means and methods" of measurement where the measurements are deeply embedded in the process.

The total Bureau experience has amply demonstrated that one cannot learn to measure without "hands on" experience, and every attempt to attack measurement problems on a purely theoretical basis has proved less than satisfactory. Therefore, in cooperation with the Bureau of Engraving and Printing, an NC machining center was set up in the NBS Instrument Shop to explore the measurement problems involved in assuring part dimensional accuracies by machine calibration. It was soon shown that the calibration techniques and software correction algorithms for static errors developed on coordinate measuring machines could be applied to machine tools in a shop environment. A five-fold increase in accuracy was demonstrated. *Figure 3* illustrates the degree of correction obtained for a milling center.

The correction of dynamic errors such as thermal distortion due to internally generated heat or distortion due to cutting forces needs further research, but appears to present no insurmountable obstacles. Certain complex dimensional measurements such as drill condition and tool setting are needed, but modern microcomputer based technology appears adequate to the task.

The AMRF will allow research in measurement technology to be expanded to include those system elements at the cell (multiwork station) level. The AMRF will provide a test bed where integrated manufacturing system measurement research can be performed.

The AMRF will provide a test bed for research directed toward the "establishing of standard practices". If flexible manufacturing systems are to become widely adopted in the discrete parts industry where 87% of the firms employ less than 50 persons, they must become much more modular then they are today. It must become possible for a firm to start with an NC machine, add a robot, add another machine, and so on as capital is accumulated and as the firm's business grows. Systems must also be capable of being tailored to various part mixes without extensive engineering effort. However, before this degree of flexibility can be accomplished, interface standards must be adopted so equipment of diverse origin can be integrated incrementally into the systems.

The first steps in this direction have already been taken. Under Air Force Integrated Computer Aided Manufacturing (ICAM) sponsorship, the NBS coordinated the efforts of a consortium of 45

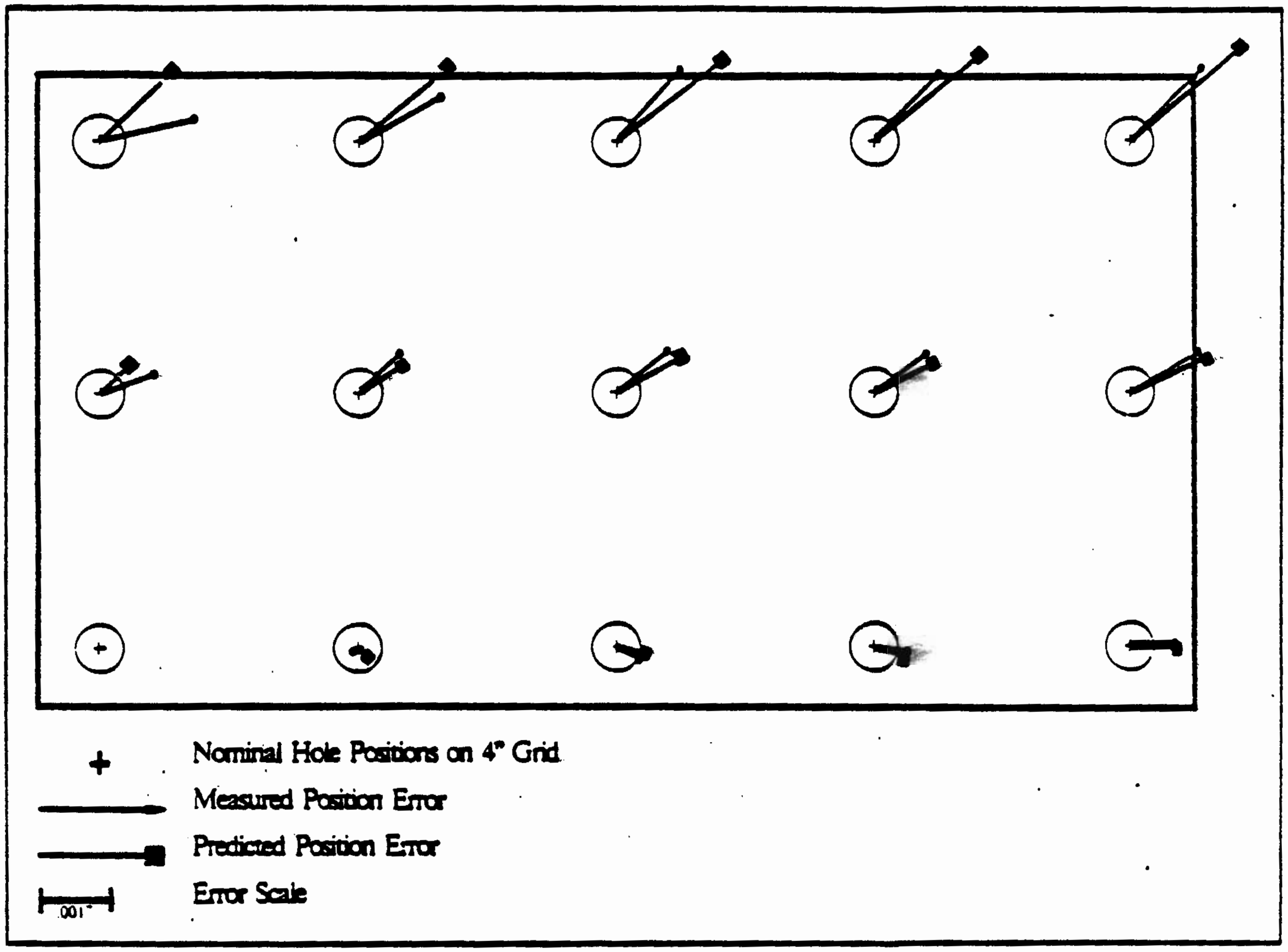

Figure 3.
The Error Map of the X-Y Plane of a Machining Center. Shown are the actual performance, measured from a hole plate compared with predicted performance obtained by measurements using laser interferometry.

private firms to generate the Initial Graphic Exchange Specification[3] (IGES). IGES is a common public domain data format which allows geometric data to be exchanged between two different types of computer aided design systems, or between a computer aided design and a computer aided manufacturing system. IGES thus allows access to the geometric data bank of a computer aided design system without the necessity of producing a drawing. IGES has recently been incorporated into a national standard (ANSI Y14.26M). The development of this standard is important for its intrinsic value; but perhaps more important, it has demonstrated that such interface standards can be structured and generated in a manner which provides full protection for proprietary interests. The AMRF will provide a test bed for the development of similar interface standards for integrated manufacturing systems. It will allow the test and verification of interface standards in an open and nonproprietary atmosphere.

Description of the AMRF

The Automated Manufacturing Research Facility will superficially resemble a FMS designed to handle the bulk of the part mix now manufactured in the NBS Instrument Shop. This part mix has been studied using Group Technology[4] concepts and is shown to be similar to a typical job shop. The parts manufactured will fall within the following limitations:

1. Weight: Less than 50 kilograms (100 lbs).
2. Size, Prismatic: 300 mm cubes (12" x 12" x 12").
3. Size, Rotational: 250 mm diameter x 250 mm length (10" x 10").
4. Parts Run: 1 to 1,000 pieces.
5. Complexity: Up to 4 axes prismatic.
6. Materials: Steel, stainless steel, aluminum, brass, iron, lucite.

The AMRF and the research performed on it will address only the manufacture of individual parts by chop forming metal removal. Hence, the unit operations will include only: fixturing, milling, drilling, reaming, tapping, boring, turning, facing, threading, cleaning, deburring, and inspection. Such problems as automated assembly, welding, hardening, and finishing will not be addressed.

The AMRF hardware is structured around the concept of single self-contained work stations, each with a well defined set of functions which can be useful as a stand-alone entity. The current plan calls for the existence of eight such stations with varying degrees of complexity of function. They are:

1. Horizontal Machining Station.
2. Vertical Machining Station.
3. Turning Station.
4. Cleaning and Deburring Station.
5. Inspection Station.
6. Materials Inventory Station.
7. Transfer System (station).
8. Housekeeping System (station).

Items 7 and 8, the Transfer and the Housekeeping Systems are not strictly stations since they are nonlocalized in the facility. From the point of view of the control system, however, they will be treated as stations.

The Materials Inventory Station will be used as a buffer to allow storage of sufficient material for several days of operation and an automatic inventory for much of the raw material requirements of a job shop. If such a system were to serve simply as a buffer, ony three or four days storage would be required, that is, enough for automatic operation through a long weekend. Since it is not the purpose of this program to study such systems *per se*, one week of storage was chosen as a reasonable trade off between the requirements of the simple buffer (or interface to the manual world) and a much more elaborate total system inventory. At this stage we plan to use the inventory system for the storage of raw material blanks, tools and tool holders (assembled), special fixtures, and finished parts or parts in-process. The inventory system will be loaded and unloaded manually while the facility is in operation.

The Materials Transport System will provide the means of moving parts, tooling, and fixtures within the facility. Two mechanisms will be used. One, a carousel, will also serve as the inventory system. The second, a robot cart or automated guided vehicle (AGV), will allow great flexibility in layout and easy access to the machines[5]. Although, the transfer system itself is not seen as a primary research area for NBS, the interfaces between the work stations and the transfer system will be designed to accommodate many different types of systems as well as other options in order to maintain modularity.

The machine tools were chosen to be representative of the types of general purpose machine tools in common use throughout the U. S. The choice also matches the specific needs of the NBS Instrument Shops as revealed by the Group Technology Study. Each of the machines will be configured into a work station with a single industrial robot.

NBS has chosen to use standard, modern, general purpose machine tools in the construction of the AMRF. This is a different strategy than that taken by two other well known national programs in automated batch manufacturing, the British A.S.P. plan[6], and the Japanese MUM or FMC plan[7]. Both of these other programs have assumed *a priori* that current machine tool designs are inadequate for an automated research facility. However, based on an international study of the state-of-the-art in machine tool science[8], NBS has decided that this assumption is highly questionable. We have chosen to rely on the engineering experience of a well-developed industry rather than a radical new design. Should problems arise in reliability, reparability, and chip removal, we plan to subcontract any needed modifications to the same industry.

Cleaning and deburring was made into a separate function (and station) because of the importance of this task for automatic inspection. As many deburring operations as possible will be carried out at the machining site. Nevertheless, there appears to be no way to avoid cleaning and deburring as a separate operation in all cases. Studies have revealed that the cost for cleaning and deburring in batch manufacturing is high and often unrecognized[9].

The Inspection Station will be a modified four axes horizontal arm measuring machine tended by a robot. It will be very similar to the machining work stations from the control point-of-view. This configuration was chosen primarily for flexibility in use.

The Housekeeping System will provide for the removal of chips during automated operation. Cleanliness during manufacturing and fixturing, and the effects of cutting fluid and chips (dust) on sensors have been serious problems in many of the existing FMS systems[10]. In the AMRF, chip removal is expected to be complicated by the variety of materials, the large number of sensors contemplated, and the decision to address the flexible fixturing problem robotically at the machines. A plan regarding chip removal is being developed at this time through both external[11,12] and internal studies. This system will be kept as simple as possible with little attempt to optimize for long unattended runs.

Layout for the facility is shown in *Figure 4*. This configuration allows easy access to the machines, and the transfer mechanism can be either the automatically guided vehicle system or the central carousel system. Coolant and cutting fluid are recycled at the machine. Buffering is provided to the machines through the row of "file-cabinets" which make up the carousel shown in the center of the model.

The three robots in the lower right are part of the cleaning and deburring station. The separate room at the upper right is the inspection station. The four machining stations each consist of an industrial robot, a machine tool, a localized inventory of tools, fixtures, grippers (end effectors), probes, and interfaces to the transfer and housekeeping systems.

The proposed operational scenario places severe requirements upon the work station and its subelements. Some of these are necessitated by the decision not to palletize and others by the wide part

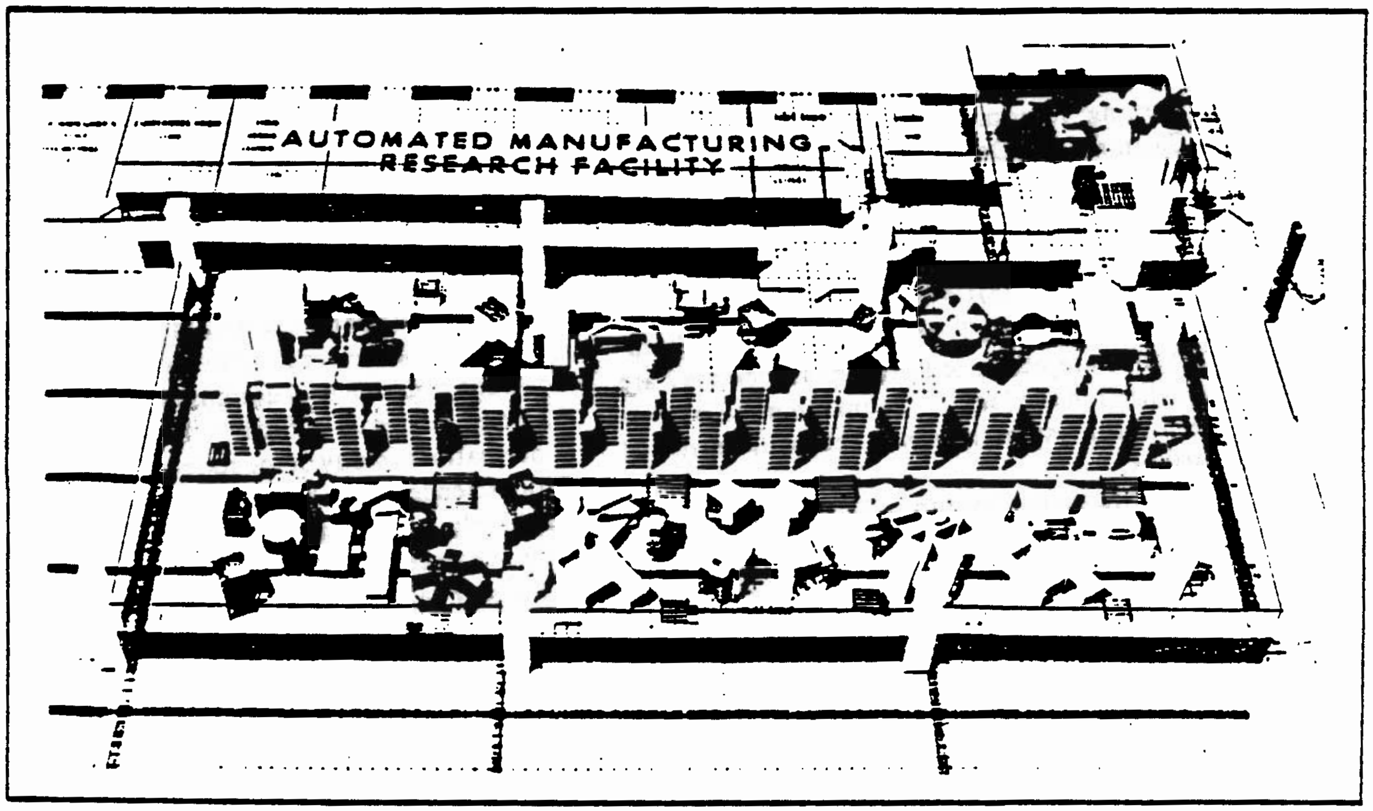

Figure 4
Model of AMRF Showing Location in Instrument Shop.
The centrally located carousel will be used to convey material, tools and finished parts. For purposes of environmental control the measuring station is, as shown, in a separate room.

mix envisioned. The tools and material arriving at a work station will not be precisely located in space. This will require advances in the state-of-the-art over current industrial robot capabilities. The robot capabilities will also be stretched by the requirement of fixturing on the machine. The problems of chip buildup and tool wear will be aggravated by the material and part mix contemplated. It is our belief that those requirements will be the norm in second generation FMS systems which will be available in the 1990s.

Table 1 gives a partial list of the functions required of the robots and machine tools in the AMRF. As can been seen, it is intended that the industrial robot be able to locate parts, tools and fixtures, transfer these items to the machine tool, fixture the part, and monitor the process while machining is carried out. Thus the robot will have extended sensory capabilities, the ability to precisely grip and position variable shapes, and considerable manipulative ability to fixture the parts upon the machine tool. In general, solutions to these problems are more difficult for prismatic than for cylindrical workpieces.

To the best of our knowledge, no one has addressed the flexible fixturing problem in any depth though some very elaborate and expensive solutions have been proposed by Tuffensammer[13]. Tool setting on machining centers is in a similarly undeveloped stage, as is generic tool wear/breakage sensing[14]. Our project plan has been to delineate as carefully as possible those areas requiring development, research carefully the state-of-the-art in these areas, and if required, initiate research directed towards the appropriate goal(s).

At present the Center for Manufacturing Engineering has two projects, one in robotics, the other in precision machining. These projects are directed towards the development of the major subsystems required for the AMRF. The integration of these two programs will take place first in the Horizontal Machining Work Station which will be the first work station to be assembled. The architecture and control system hardware for this work station will serve as a model for the other four generically similar work stations.

Although it is recognized that there are important problems of CAD/CAM integration to be solved, the current plans do not include work in this area. Production and process planning systems needed to load the facility will be the largely manual processes currently used for the NC station of the instrument shop.

Table 1
Functions of the Work Station Subelements

Robots Arm Functions

1. Part loading and unloading.
2. Tool loading and unloading.
3. Rough (± 50 mil) part fixturing or fixture assembly.
4. Chip removal and control.
5. Coarse visual inspection of fixtures and parts.
6. Initial part and tool location.
7. End effector selection.
8. Deburring and cleaning (only as needed for next operation).
9. Safety.
10. Self-monitoring.

Machine Tool Functions

1. Machining.
2. Part locations.
3. Tool wear/breakage sensing.
4. Tool setting/checking.
5. Process monitoring (cutting).
   a. Dynamics.
   b. Thermal.
   c. Hydraulics (etc.)
6. Self-monitoring.
7. Deburring and cleaning (as part of the machining operation).
8. Adaptive control.

Control Architecture of the AMRF

In order for the AMRF to serve as a research facility over the next decade, it must exhibit a higher order of flexibility than any currently available FMS. It must not only be capable of very wide part mix, but must also be capable of easy reconfiguration to emulate work stations or small cells operating in the environment of a much larger and perhaps unmanned system. To accomplish these goals requires a control system architecture of considerable sophistication. The conventional Direct Numerical Control (DNC) top down architecture was judged to be unsuitable, primarily because of the inability of such a system to react to feedback from sensors in real-time. In order for an entire machine shop to completely operate automatically, all the machines must be equipped with sensors to monitor their performance and compensate for irregularities and uncertainties in the work environment. The sensor data must be processed and analyzed, and the results introduced into the machine control systems in real-time so that the response of each machine is goal-directed, reliable, and efficient.

A high degree of sensory-interactive behavior on the part of individual machines creates enormous system control problems for an entire shop. The problem of automatically controlling a number of feedback driven machine tools is much bigger than simply the sum of the control problems for the individual machines. The interactions among many *sensory-interactive machines* creates a system control problem in which complexity grows exponentially with the number of individual machines and sensor systems. Once there are more than a few machines, each reacting to sensor data in real-time, the overall system control problem can become completely unmanageable. This is the point at which most of the early attempts at building the automatic machine shop failed. The control software for such a system can become enormously complex to write and virtually impossible to debug. The classical solution to control problems of this complexity is to partition the problem into modules and introduce some type of hierarchical command and control structure. The advantage of hierarchical control is that it allows the control problem to be partitioned so as to limit the complexity of any module in the hierarchy to manageable limits, regardless of the complexity of the entire structure.

The use of hierarchical control for industrial applications is not new. It has been employed in controlling complex industrial plants such as steel mills, oil refineries, and glass works for years. However, such hierarchies are usually limited to two or three levels and; most often represent fairly straightforward servo control applications. The unique features of the control system being planned for the AMRF are the number of hierarchical levels (perhaps as many as seven or eight), and the amount of real-time computation and sensory-interaction at each level. Each hierarchical level will perform a significant amount of real-time computation and will interact dynamically with the shop environment in many different ways. The plan is to build a real-time sensory-interactive control system which at the lower levels will respond to events of millisecond duration (tight servo loops), and at the upper levels will react to events of days or weeks duration (production planning and scheduling problems). The levels in between these extremes will produce intelligent automatic responses to many different types of shop floor conditions and situations.

Figure 5 illustrates the basic logical and temporal relationships in a hierarchical computing structure. This particular example illustrates the control structure for an industrial robot. However, the concepts are readily generalized and will be applied to the entire AMRF.

On the left of *Figure 5* is an organizational hierarchy wherein computing modules are arranged in layers. The basic structure of the organizational hierarchy is a tree. The flow of command and control is vertical. Each node in the tree represents a computing module which receives input commands from only one supervisor module (predecessor node) and issues subcommands to one or more subordinate modules (successor nodes). There may be information flow regarding sensory inputs and internal contextual and sequencing data that flow horizontally and/or rise from lower levels in a cross-coupled network of communication channels, but the primary command and control pathways form a strict hierarchical tree.

At the top of the hierarchy is a single high-level computer module. Here at the highest level, most global goals are decided upon and long-range strategy is formulated. Feedback to this level is integrated over an extensive time period and is evaluated against long-range objectives. Here long-range plans are formulated to achieve the highest priority objectives. Decisions made at this highest level commit the entire hierarchical structure to a unified and coordinated course of action which would result in the selected goal or goals being achieved. At each of the lower levels, computing modules decompose their input commands in the context of feedback information generated from other modules at the same or lower levels, or from the external environment. Sequences of subcommands are then issued to sets of subordinates at the next lower level. This decomposition process is repeated at each successively lower hierarchical level, until at the bottom of the hierarchy there is generated a set of coordinated sequence of primitive actions which drive individual actuators such as motors of hydraulic pistons in generating motions and forces in mechanical members.

Each chain-of-command in the organizational

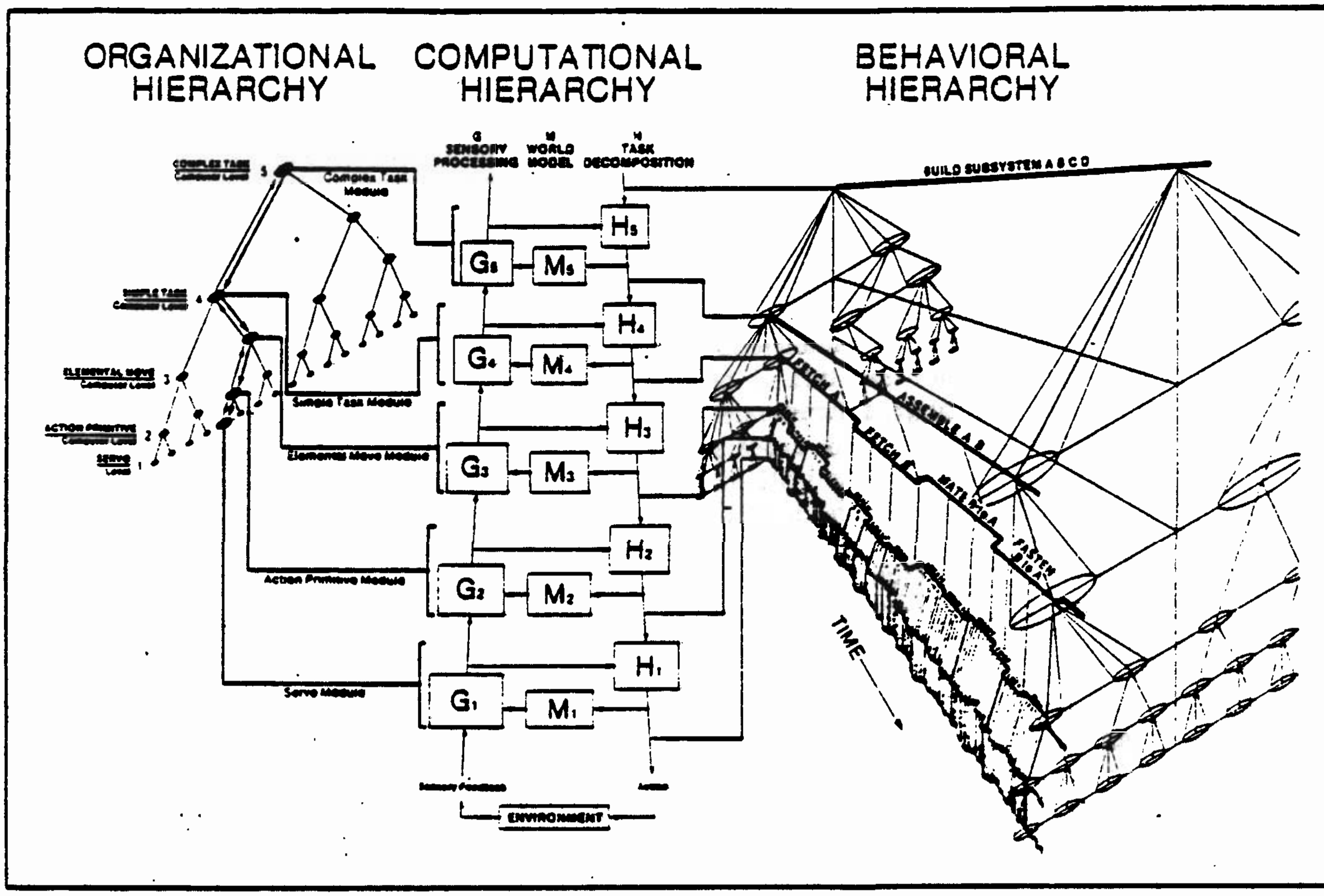

Figure 5
Control System Hierarchy for a "Smart" Robot

hierarchy consists of a computational hierarchy of the form shown in the center of *Figure 5*. This computational hierarchy contains three parallel hierarchies: (1) a task decomposition hierarchy which decomposes high-level tasks into low level actions, (2) a sensory processing hierarchy which processes sensory data and extracts the information needed by the task decomposition modules at each level and (3) a world model hierarchy which generates expectations of what sensor data should be expected at each level based on what subtask is currently being executed at that level.

Each level of the task decomposition hierarchy consists of a processing unit which contains a set of procedures, functions, or rules for decomposing higher level input commands into a string of lower level output commands in the context of feedback information from the sensory processing hierarchy. At every time increment each H module in the task decomposition hierarchy samples its inputs (command inputs from the next higher level and feedback from the sensory processing module at the same level) and computes an appropriate output. A detailed description of such a system as applied to robots has been published elsewhere[15,16,17].

The sophisticated real-time use of sensor data for coping with uncertainty and recovering from errors requires that sensory information be able to interact with the control system at many different levels with many different constraints on speed and timing. Thus in general, sensory information at the higher levels is more abstract and requires the integration of data over longer time intervals. However, behavioral decisions at the higher levels need to be made less frequently, and therefore the greater amount of sensory processing required can be tolerated.

Attempting to deal with this full range of sensory feedback in all of its possible combinations at a single level leads to extremely complex and inefficient programs. The processing of sensor data, particularly vision data, is inherently a hierarchical process. Only if the control system is also partitioned into a hierarchy can the various levels of feedback information be introduced into the appropriate control levels in a simple and straightforward manner.

The world model hierarchy contains prior knowledge about the task, the parts, and the work environment. Typically, the type of feedback information required by the task decomposition modules at each level depends upon what task is being performed. As conditions change, different sensors, different resolutions, and different processing algorithms may be needed. Given the state of the task execution at each level, the world model can predict what kind of sensory processing algorithms should be applied to the incoming data. Furthermore, sensor data can often be predicted from the actions being executed by the control system.

The world model generates expectations as to what the sensor data should look like. These predictions may be based on previous experience when a similar task was performed on a similar part, or may be generated from a Computer Aided Design (CAD) data base which contains a geometrical representation of the part. The world model hierarchy may contain information as to the shape, dimensions, and surface features of parts and tools and may even indicate their expected position and orientation in the work environment. This information assists the sensory processing modules in selecting processing algorithms appropriate to the expected incoming sensor data, and in correlating observations against expectations. The sensory processing system can thereby detect the absence of expected events and measure deviations between what is observed and what is expected.

Feedback can be used by the task decomposition hierarchy either to modify action so as to bring sensory observations into correspondence with world model expectations, or to change the input to the world model so as to pull the expectations into correspondence with observations. In either case, once a match is achieved between the two, the task decomposition hierarchy can act on information contained in the model which cannot be obtained from direct observation. For example, a robot control system may use model data to reach behind an object and grasp another object which is hidden from view.

If the symbolic commands generated at each level of the task decomposition hierarchy are represented as points in the multidimensional "state-space" consisting of the coordinates of all the degrees of freedom of the machine or robot, and these points are plotted against time, the behavioral hierarchy shown on the right of *Figure 5* results. The lowest level trajectories of the behavioral hierarchy correspond to observable output behavior. All the other trajectories constitute the structure of conditions deep within the control programs.

At each level in the behavioral hierarchy, the string of commands makes up a program. This architecture implies that there is a programming language unique to each level of a hierarchial control system, and that the procedures executed by the computing modules at each level are written in a language unique to that level. This partitioning of the control problem into hierarchial levels limits the complexity of the programming language and the programs at each level. It also generates a whole hierarchy of languages for programming the robots, machine tools, and inspection systems, and for performing, planning and scheduling operations. It is to be noted that such a hierarchy lends itself to the utilization of IGES-type interface standards at each level.

If the control problem is further partitioned along the time axis, an additonal degree of simplicity can be achieved. If time is partitioned into a finite number of computational periods, each computational module can be represented as a finite-state machine. At every time interval, each computational module samples its inputs (command and feedback) and computes an output. The programs resident in each of the computational modules then become simple functions which can be represented by formulae of the form $P=H(S)$, or by a set or production rules of the form IF<S>, THEN<P>. The control structure becomes a simple search of a state transition table.

Each entry in the state-table represents an IF/THEN rule, sometimes called a production. This construction makes it possible to define behavior of high complexity. An ideal task performance can be defined in terms of the sequence of states and state transition conditions that take place during the ideal performance. Deviations from the ideal can be incorporated by simply adding the deviant conditions to the left-hand side of the state-table and the appropriate action to be taken to the right-hand side. Any conditions not explicitly covered by the table results in an "I don't know what to do" failure routine being executed. Whenever that occurs, the system simply stops and ask for instructions. If the condition can be corrected, a human programmer can enter a few more rules into the state-table and the system can continue. By this means, the system gradually learns how to handle a larger and larger range of problems. This extensibility of the system to new problems is essential in a research facility which, by its very nature, will usually oprate at the very limits of the current state of knowledge.

Such a finite-state machine hierarchical control system has been implemented on a microcomputer network. This network, shown in *Figure 6* has been under evaluation as a control system for the robots in the AMRF[15].

The logical structure of *Figure 5* is mapped into the physical structure of *Figure 6*. The coordinate transformations of *Figure 5* are implemented in one of the microcomputers of *Figure 6*. The elemental move trajectory planning is implemented in a second microcomputer of *Figure 6*. The processing of visual data is accomplished in a third microcomputer, and the processing for force and touch data in a fourth microcomputer. A fifth microcomputer provides communication with a minicomputer wherein reside additional modules of the control hierarchy. It is anticipated that these will eventually be embedded in a sixth microcomputer.

Communication from one module to another is accomplished through a common memory "mail drop" system. No two microcomputers communicate directly with each other. This means that common memory contains a location assigned to

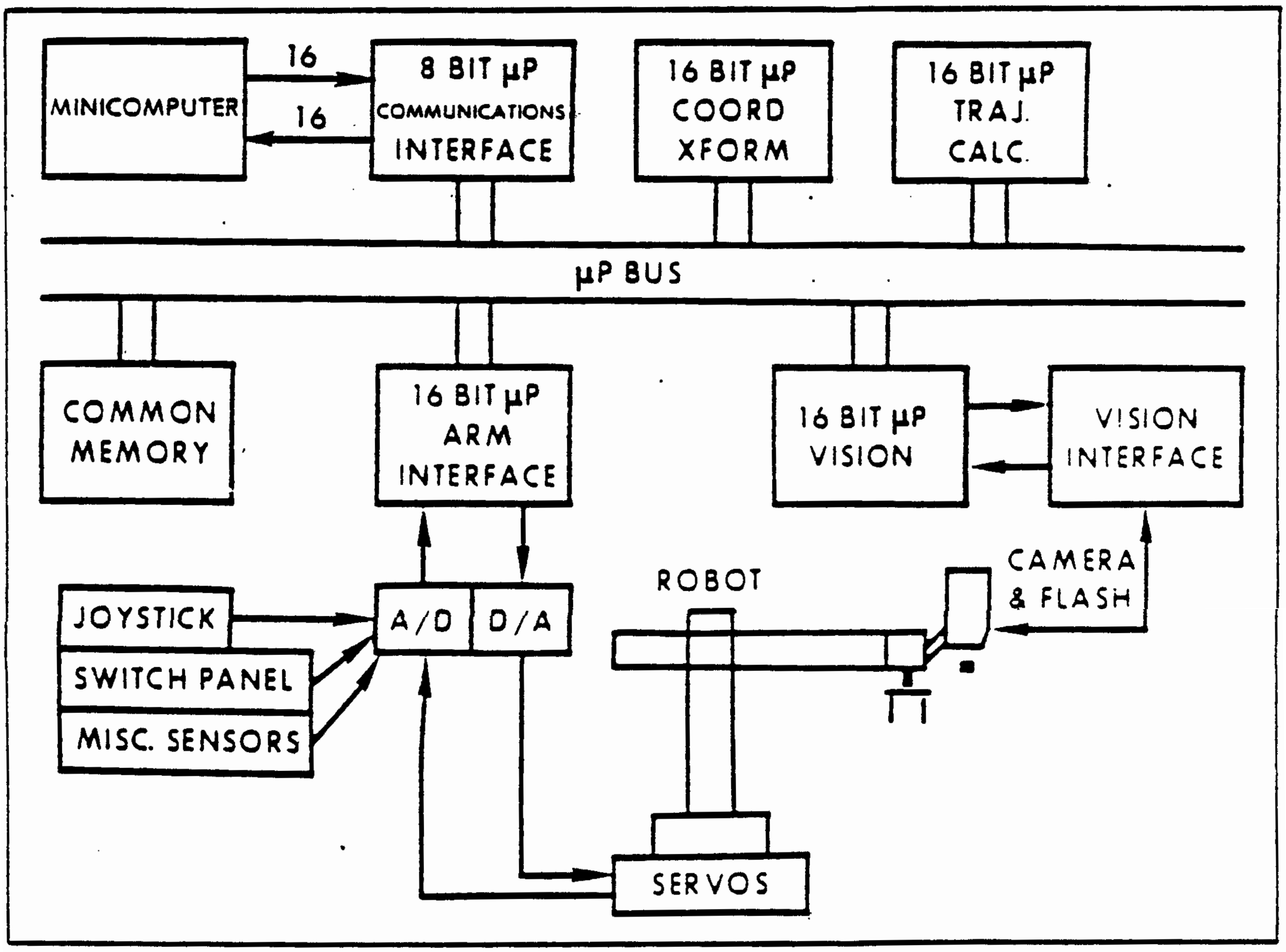

Figure 6
Realization of Hierarchy Utilizing Microcomputer Network with Common Memory for Communication

every element in the input and output vectors of every module in the hierarchy. No location in common memory is written into by more than one computing module, but any number of modules may read from any location.

Time is sliced into 28 millisecond increments. At the beginning of each increment, each logical module reads its set of input values from the appropriate locations in common memory. It then computes its set of output values which it writes back into the common memory before the 28 millisecond interval ends. Any of the logical modules which do not complete their computations before the end of the 28 millisecond interval write extrapolated estimates of their output accompanied by a flag indicating that the data is extrapolated. The process then repeats.

Each logical module is thus a state-machine whose outputs depend only on its present inputs and its present internal state. None of the logical modules admit any interrupts. Each starts its read cycle on a clock signal, computes and writes its output, and waits for the next clock signal. Thus, each logical module is a finite-state machine with the IF/THEN, or P=H(S) properties of an arithmetic function.

The common memory "mail drop" communication system has a number of advantages and disadvantages. One disadvantage is that it takes two data transfers to get information from one module to another. However, this is offset by the simplicity of the communication protocol. No modules talk to each other so there is no handshaking required. In each 28 millisecond time slice, all modules read from common memory before any are allowed to write their outputs back in.

The use of common memory data transfer means that the addition of each new state variable requires only a definition of where the newcomer is to be located in common memory. This information is needed only by the module which generates it so that it knows where to write it, and by the modules which read it so that they know where to look. None of the other modules need know, or care, when such a change is implemented. Thus, new microcomputers can easily be added, logical modules can be shifted from one microcomputer to another, new functions can be added, and even new sensor systems can be introduced with little or no effect on the rest of the system. As long as the bus has surplus capacity, the physical structure of the system can be reconfigured with no changes required in the software resident in the logical modules not directly involved in the change.

Furthermore, the common memory always contains a readily accessible map of the current state of the system. This makes it easy for a system monitor to trace the history of any or all of the state variables, to set break points, and to reason backwards to the source of program errors or faulty logic.

The read-compute-write-wait cycle wherein each module is a state-machine makes it possible to stop the process at any point, to single step through a task, and to observe in detail the performance of the control system. This is extremely important for program development and verification in a sophisticated, real-time, sensory-interactive system in which many processes are going on in parallel at many different hierarchical levels.

The hierarchical control structure just described is a generic concept which can be extended to apply to a wide variety of automated manufacturing systems. NBS plans to use this conceptual framework for the control system and data base architecture for the AMRF. *Figure 7* is a block diagram of the control system planned for the AMRF. The square boxes arranged in the hierarchical structure in the center of the figure represent the task decomposition modules at the various levels of control.

At the lowest level in this hierarchy are the individual robots, N/C machining centers, smart sensors, robot carts, conveyors, and automatic storage and retrieval systems, each of which may have its own internal hierarchical control system. The bottom row of boxes represents the control systems for these individual machines. The small subboxes labeled S and C correspond to the sensory and command interfaces to these control systems. The command input to the robot in *Figure 7* corresponds to the H3 Elemental Move Module input in *Figure 5*.

The bottom row of control modules in *Figure 7* is organized into work stations under the second row of work station control modules. A work station may consist of a machine tool, a robot, and a set of smart sensors. It may also consist of a set of robot carts, or an automatic storage and retrieval system with its associated robot. A machine work station control module accepts input commands of the form <MACHINE PART X>. A material handling work station may accept commands of the

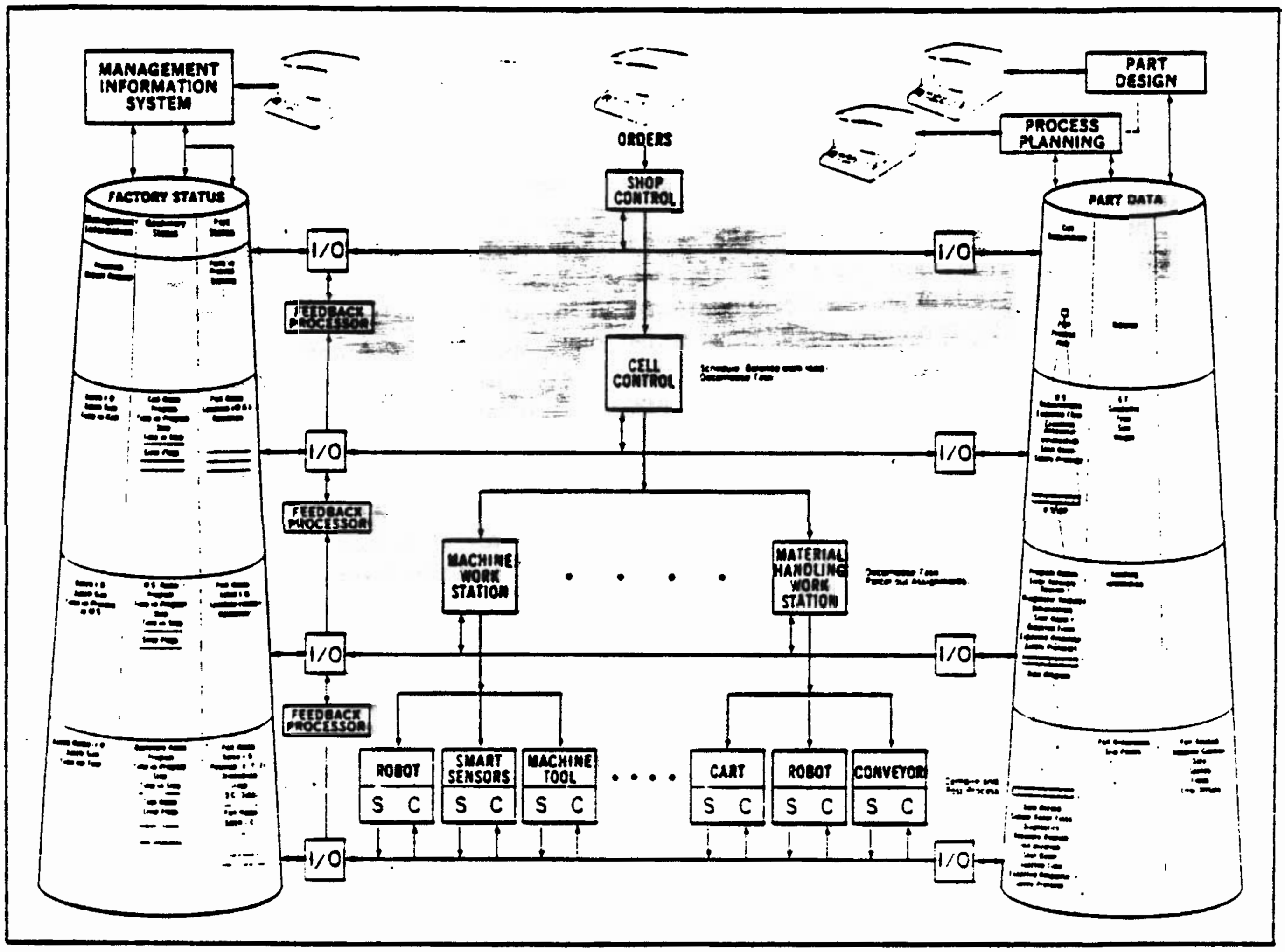

Figure 7
Schematic of Hierarchical Control as Applied to the Factory of the Future

form <MOVE TRAY Y TO WORK STATION Z>. The machine work station controller decomposes its commands into sequences of subcommands to the machine controllers of the form <FETCH PART X>, <INSERT X IN FIXTURE Y>, <EXECUTIVE CUTTING PROGRAM Z>, <CLEAR CHIPS>, etc. The material handling work station decomposes its commands into sequences of subcommands of the form <DISPATCH CART A TO PICKUP STATION B>, etc. In both cases, the decomposition is performed in the context of feedback information that is passed through the factory status data base shown on the left of *Figure 7*.

The work station controllers may contain programs written in the form of state-tables, or production rules. This formulation will allow the behavior of the work station to adapt to unexpected conditions such as broken tools or defective or missing parts.

Several work station control units are organized under and receive input commands from a cell control unit. The cell controller schedules jobs, routes parts and tools to the proper machines, and balances the workload among the work stations under its control. The cell controller makes sure that each machine has the proper tools at the proper time to perform the required work on each part.

Programs in the cell controller are also written in state-table form and can contain any number of rules for adapting to error conditions such as tool failures or changing priorities.

Several cells could be organized under a shop control unit. However, the AMRF initially at least, will be considered as a single cell, and hence only one cell controller is planned. The possibility exists for either further expansion of the AMRF or emulation of other cells if the research task demands it.

There are two data bases planned for the AMRF. On the right of *Figure 7* is a Part Data Base which contains design data such as part dimensions, desired grip points for robot handling, group technology codes, and material and tooling requirements. A second section of the right-hand data base contains process plans for routing and scheduling and robot handling as well as cutter location data files needed for performing the various machining operations. These process plans are, in fact, the programs required at the various levels of the control hierarchy in order to perform the necessary manufacturing operations. Thus, the right-hand data base is, in part, a program library which contains the control programs needed by the control modules at the various levels of the control hierarchy. A third section of the right-hand data base contains data related to feeds and speeds which may be changed as a result of sensed conditions in the factory environment.

When an order is entered into the shop control module, the process plan to make that part is called in from the right-hand data base. The process plan is hierarchically structured so that at the top there is only the name of the process plan. This name is sent to the cell control. The cell control computer accesses the data base which calls in the sequence of steps (i.e., the program) that is the process plan at the cell level. Each command in this program is passed in sequence to the next level down, which is the work station. As each cell output command enters the work station, it is the name of a process plan for the work station. The work station then goes to the part data base as its level and calls up the sequence of instructions required to decompose that process plan for the robot or for the machine tool.

The data that reside in the part data base come from an interactive design graphics system and an interactive process planning system shown at the top right of *Figure 7*.

On the left of *Figure 7* is a second data base which contains dynamic Factory Status information. This Factory Status data base is also divided into three parts. On the far left is a management information and control data base. Entries or queries to and from this data base enable management to monitor and manage the whole factory by setting priorities or entering control parameters which alter the mode of operation of the control hierarchy.

The second section of the Factory Status data base contains the status of each machine tool and robot in the plant as well as the status of each computer in the control hierarchy: What program is each machine running? What step in the program? How long in that step? What part is being operated on?, etc.

The third section of the Factory Status base contains the status of each part in progress. In this data base, there exists a data file corresponding to every part that gives the part name, the tray that is transporting it, its position and orientation in that tray or in the work station, its state of completion, and a number of quality control parameters.

All these data bases are served by several Input/Output (I/O) controllers. The Factory Status data base also has a hierarchy of feedback processors that scan the various levels of the data base and extract the information needed by the control modules at the next higher level. As in the microcomputer robot control network, information is passed from one level to another, and from one computing module to another through the data base which serves as a common memory. This makes the system modular and defines the interface between modules to be the data base. Thus, specification of the data base specified the principal interfaces of the control system. This means that as long as a robot or machine tool controller can read from and write to the data base, it can be added to or deleted from a system with a minimum of impact on the other components of the system.

Because the status data base will be updated at each time increment, it will always contain a complete and current state description of the entire factory. This will make it possible to restart the system easily in the event of a computer system crash. It will also be useful as a debugging tool. Activities of the various modules and of the system variables themselves can be traced and recorded for debugging, analysis, or optimization.

The control architecture has been described in considerable detail since it is this feature that most clearly distinguishes the AMRF from "just another FMS". This system will provide the modularity needed to carry out the NBS research program in interface standards and will eventually make FMS technology practical for many smaller shops.

Concluding Remarks

Although it will require a certain amount of research to construct the AMRF and to test the concepts on which it is based, the AMRF itself is not considered a research project. As various portions come on line, research projects, often with university or private sector cooperation, will be started. Many of these projects will deal with new and improved sensors to monitor machine performance. Others will deal with the problem of calibrating sensors so that the product dimensions (not the sensor responses) are traceable to National Standards. If more than one machine is involved in the manufacture of a part so that the refixturing effects the critical dimensions, this traceability becomes a complex problem. How both the mechanical operations and their supporting software are validated opens vast new areas for Measurement Assurance Program technology. Along with this metrology research will go research on the detailed nature of the data formats at each interface to determine how standards can be designed so as to neither compromise proprietary interests, nor inhibit innovations. The AMRF, like other Bureau facilities, will be made available to university and industrial groups for nonproprietary research in manufacturing engineering which lies further afield than the metrology and standards of NBS.

The AMRF is only one in a continuing series of facilities that permit NBS to fulfill its designated role as the nation's measurement and standards laboratory.

Acknowledgements

The Automated Manufacturing Research Facility* owes its existence to the foresighted management of the National Bureau of Standards and the Department of Commerce, and the support and encouragement of the machine tool community, especially those who have joined in the program as Research Associates. The support of the Department of Defense at various points in the program has been most helpful as has been the university community working with us both informally and under what is hoped to be an expanding grants program. The AMRF is truly a National effort.

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Author(s) Biography

Dr. John A. Simpson is presently Director of the Center for Manufacturing Engineering at the National Bureau of Standards (NBS), with background in the fields of dimensional metrology, electron optics, photo-optical instrument design, and mechanics. Prior to his appointment to this position, Dr. Simpson served as Chief of the Mechanics Division, Deputy Chief of the Optical Physics Division, and Chief of the Electron Physics Section, all at NBS, and was a Research Physicist at Lehigh University.

Dr. Simpson is a Fellow of the American Physical Society and has been active in its Division of Electron Physics. He has served on the National Academy of Sciences/National Research Council Panel for NATO Postdoctoral Fellowships. In 1975, he received the Department of Commerce Gold Medal award in recognition for his accomplishments in modernizing the metrology services of NBS. In 1980, he received the NBS Applied Research Award (jointly) for his part in the development and implementation of the automated, self-correcting three-axis coordinate measuring machine which enables manufacturers to characterize and correct errors in machine tools during manufacturing processes.

Dr. Robert J. Hocken is presently Chief of the Automated Production Technology Division at the National Bureau of Standards, with background in the areas of critical phenomena, machine tool metrology, three-dimensional metrology, laser optics, manufacturing technology, and polarimetry. His division at NBS develops and maintains competence in machine tool dynamics, precision engineering, robotics, and computer aided manufacturing, and is concerned with the incorporation of metrology into the precision metal working processes, including the standards necessary for integration of equipment up to the manufacturing cell level. Prior to appointment to this position, Dr. Hocken held a National Research Council Postdoctoral position at NBS, was Leader of the Dimensional Metrology Group, and Chief of the Dimensional Technology Section at NBS.

Dr. Hocken is a member of the American Physical Society, the American Society for Testing and Materials, and the International Institute for Production Engineering Research. He is a widely recognized expert in production metrology and recipient of the Taylor Medal of CIRP for contributions to metrology, the Department of Commerce Silver Medal for three-dimensional metrology, the IR-100 Award for the large-scale measuring machine, and the NBS Applied Research Award (jointly) for the development of the three-axis measuring machine which enables manufacturers to characterize and correct errors in machine tools during manufacturing processes.

Dr. James S. Albus is presently Acting Chief of the Industrial Systems Division and Manager of the Programmable Automation Section, Center for Manufacturing Engineering, National Bureau of Standards. He has received the Department of Commerce Silver Medal for his work in control theory and manipulator design and the Industrial Research IR-100 award for his work in brain modeling and computer design. He is the author of numerous articles in technical journals including a survey article on robot systems for *Scientific American* (February 1976) and an entry to *Encyclopedia Americana on "Robots"*. He has written articles on robotics for *OMNI* Magazine, *Metal Working News*, and *BYTE* Magazine. Dr. Albus has also been quoted in other national magazines, such as *TIME, Fortune, Reader's Digest, NEXT*, and *Discover*, and has appeared in a number of TV interviews.

Before coming to the Bureau of Standards, he designed electro-optical systems for more than 15 NASA spacecraft, seven of which are on permanent display in the Smithsonian Air and Space Museum. For a short time he served as program manager of the NASA Artificial Intelligence Program.

His latest book *Brains, Behavior and Robotics* was published by McGraw-Hill in November 1981. Dr. Albus has also written a book entitled *Peoples' Capitalism: The Economics of the Robot Revolution* in which he addressess some of the central social and economic issues raised by the advent of computer controlled robot industries.

ture readings, and home positions. A record is kept of each failure.

The computer-aided process planning (CAPP) module is a generative program based on part codes. It lets engineers select forgings, operation sequences, and process instructions, and develop process optimization, routing sheets, and cutting feeds and speeds. The CAPP system makes use of group technology in part and tooling design and in process descriptions.

System Payoffs

The AEBG DNC has permitted a 15% increase in productivity. In process planning, for instance, engineers can shift new rotational geometries to existing forgings and geometries, sometimes avoiding the need to retool, and cutting machining time if the process is near net shape.

Additional capabilities can be incorporated into the CIM system, providing as-needed flexibility. These capabilities may include a robotic sermetal painting line, robotic application of brazing alloys, computer-controlled process parameters and part positioning for vacuum plasma deposition, and DNC laser drilling. With a system that has already increased productivity and reduced costs by as much as 25%, added capabilities can only enhance the AEBG CIM system. ■

Research in Automated Manufacturing at NBS

An update on the National Bureau of Standards' facility for automation research

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In late 1980, the National Bureau of Standards (NBS) made a decision to develop and construct an Automated Manufacturing Research Facility (AMRF) by the mid-80s to support research on machine interfacing and inspection of parts produced in small batches.

The facility is designed to serve three major sectors—industry, government, and academia—in developing, testing, funding, and implementing advances in automated manufacturing. The AMRF is a direct resource for members of the manufacturing community who wish to see demonstrations of existing and near-future technology as an aid in their own automation decisions. The project also plays a crucial role in meeting the NBS' legal commitment to leadership in standards and measurement activity, especially in a time of rapidly advancing technology. Finally, this new facility serves as a "test bed" for industrial research associates, university workers, and scientists at the NBS who are preparing the way for the computer automation technology of the next decade.

Testing and Calibration

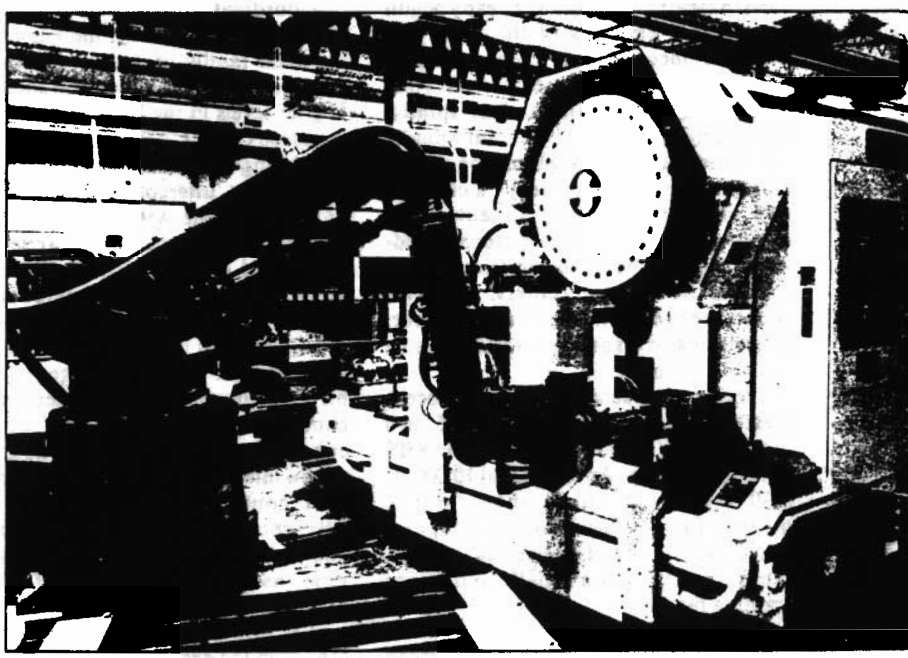
The legislation which created and governs the NBS specifically assigns to it the function of "testing and calibration of standard measuring apparatus [and] the solution of problems which arise in connection with standards." Two major problem areas related to standards are being addressed in the AMRF. These concern interchangeability of parts and interchangeability of manufacturing units. Work on the former involves dimensional accuracy and falls under the heading of deterministic metrology. Work on the latter deals with interface standards which allow easy transfer of part information between different manufacturers' equipment and easy replacement or upgrading of design and manufacturing equipment.

Deterministic Metrology. Gage blocks and other artifact standards provide the basis of a mature technology which assures accuracy by direct comparison of dimensions. For complex parts, the computer-controlled coordinate measuring machine has successfully automated such comparisons, but it still depends upon measuring the part itself.

In a well-designed automated manufacturing process, if one good part is produced and if the process parameters (such as cutting force and temperature distribution in the machine tool) are controlled or corrected, then subsequent parts cut by that same program are also likely to be good. This observation underlies the philosophy of deterministic metrology which concentrates on understanding, monitoring, and controlling the manufacturing process itself rather than checking the part after cutting is finished. Thus, the standards' responsibility which called for careful custody of master gage blocks and calibration of other artifact blocks from these masters is now advancing into a technology which requires a fundamental understanding of ways to monitor and control basic cutting processes.

Close attention to process control has led NBS scientists to work in the area of software accuracy enhancement. By developing an "error map" for a CNC machine or coordinate measuring ma-

A horizontal machining center work station within the Automated Manufacturing Research Facility of the NBS is tended by a Cincinnati Milacron robot.



chine and incorporating a correcting algorithm into its control computer, the accuracy of standard equipment can be markedly increased.

Interface Standards. In the area of interface standards, NBS scientists coordinate and support work on a common domain graphics exchange standard known as the Initial Graphics Exchange Standard (IGES). This standard, the work of an industry-wide committee, allows the transfer of CAD data between the systems of various manufacturers. Pre- and postprocessors for IGES have been announced or promised for all of the major CAD systems.

American industry has reached a consensus that it must increase its concentration on quality and productivity in order to develop and hold our country's leading position in international commerce. Thus, the NBS has found strong industry support for development of the AMRF from industry, universities, and other agencies of the government concerned with manufacturing.

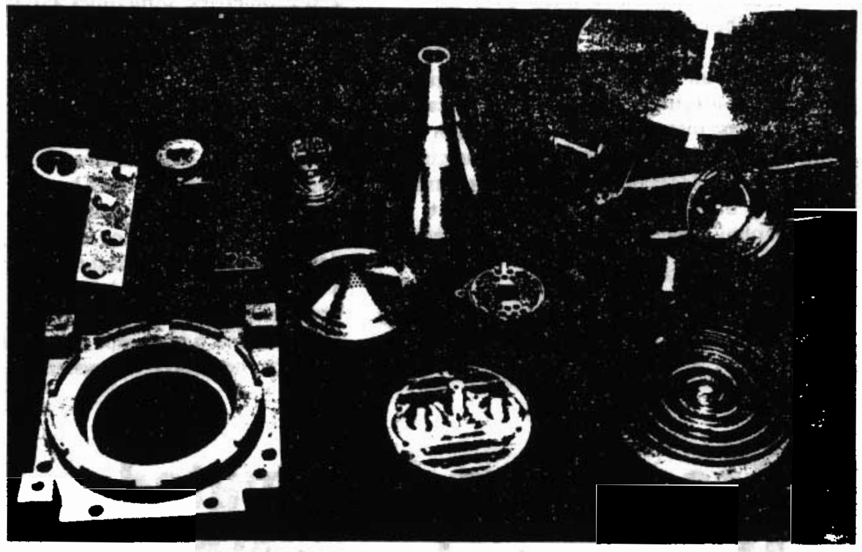
Under the NBS research program, a topic of interest to an industrial sponsor is investigated by a research associate employed by the sponsoring firm and assigned to work at NBS. Frequently, a program uses a machine tool which belongs to the sponsor, but which is temporarily incorporated into the AMRF. Such cooperative research activities serve to assure that the AMRF combines practical economic solutions to near-term problems with the capacity to advance the state of the art.

Developing the AMRF

Developmental planning, procurement, and testing of the many elements of the AMRF are expected to extend well into 1986. Research activity has already begun on modular elements of the facility as they are incorporated. The AMRF, as presently defined, consists of four machining centers (a vertical spindle machining center, a horizontal spindle machining center, a large turning center, and a smaller turning center), a cleaning and deburring station, an automatic inspection station, and a material handling complex. The two machining centers, one of the turning centers, and two robots are present now on the shop floor, the automatic inspection station will be installed by late 1983.

The AMRF machining hardware occupies approximately 5000 ft^2 (465 m^2) within the 15,000-ft^2 (1395-m^2) NBS Instrument Shop. An additional 10,000 ft^2 (930 m^2) off the main shop floor is utilized for a toolcrib area, computer space, electronic and mechanical support laboratories, and a small conference training facility.

Modular Architecture. An early decision in planning for the AMRF determined that the control architecture must be modular and designed so that it can be implemented in steps. Under this design approach, a shop or factory can undertake automation in steps which are economically tolerable and still reasonably expect the various pieces to fit together into an integrated production facility as more components are added to the system.



Serving as models for AMRF design specifications, parts like these will be produced in the NBS Instrument Shop.

The AMRF itself is being constructed in a similar step-like fashion. Before control system development advances to higher levels of demonstration, a working unit consisting of a single machining center, its robot tender, fixturing, material handling interfaces, and various sensory systems is fully developed and tested as a freestanding work station driven by manual or simulated higher-level commands.

Coordinated control of several work stations dealing, for the moment, with a common family of parts will be maintained at the cell level by a cell controller. Higher levels in the hierarchy of control integrate CAD, CAPP, MIS, and factory scheduling functions.

Machine Interconnections. A major objective of the AMRF is to study the interface problems which arise when automated equipment produced by different manufacturers is interconnected into an integrated facility. In the process of solving such interface problems, NBS scientists can propose changes in equipment to improve interconnection and control. Work with software accuracy enhancement has defined a whole range of new interface requirements for machine tool controllers. In a similar way, development of off-line programming and real-time control for robots has given new insight into the need for more sophisticated robot controller interfaces.

Various sensor types are being employed in the design of the AMRF, including force, proximity, vision, temperature, and vibration. High-precision dimensional sensing is incorporated in toolsetting stations which use linear variable differential transformers (LVDTs) that have been "hyperlinearized" by software correction techniques developed by NBS scientists.

Design of the control structure is based on distributed computing power which takes advantage of recent advances in microelectronics. Because of this design decision, a high level of computational capacity can be economically incorporated into sensory systems and other elements low in the control hierarchy. For example, a dedicated safety system with its own controller is being incorporated into each work station in order to provide redundant safety checking for the protection of both humans and machines.

Using Available Equipment. In contrast with the approach adopted in the British ASP Plan and the Japanese FMC Project, the NBS is using standard, modern, commercially available machine tools in the AMRF. The ASP and FMC approaches call for the design of new machine tools for automation. The NBS, based on reviews of published studies of the international state of the art in machine tool design, has chosen instead to rely upon the engineering experience of a mature machine tool industry and to avoid radical design changes for the AMRF machining centers and other facility hardware.

The AMRF is meant to be a national project which draws upon and contributes to work on automation of small batch manufacturing being conducted by industry, universities, and other laboratories. While the efforts of the NBS relate to problems of standards, the bureau also encourages close cooperation with those who are addressing other components of the field. ■