A Proposed Hierarchical Control Model for Automated Manufacturing Systems

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Abstract

The Automated Manufacturing Research Facility is being constructed at the National Bureau of Standards. This small, integrated, flexible manufacturing system will serve as a research test bed to aid in the identification, design, and testing of standards for the automated factory of the future. This paper describes the five layer hierarchical production control model proposed to manage these factories. Included is a discussion of the philosophy behind this model, the functional requirements of each layer within the model, a brief description of the data services needed to support this approach, and an overview of the techniques used to implement existing subsystems.

Keywords: *Automated Manufacturing, Data Services, Factory Model, Flexible Manufacturing, Hierarchical Control.*

Introduction

The advent of sophisticated automated equipment such as robots, machine tools, and transport vehicles and the proliferation of computer hardware and software have made the concept of fully automated and integrated manufacturing systems a reality. However, the incorporation of these systems into existing factories has been slower than anticipated. One of the major reasons is that there is no generic factory model upon which to base system designs and interfaces between systems. This paper describes the efforts at the National Bureau of Standards (NBS) to develop a generic architecture for real-time production control and the current level of implementation within the Automated Manufacturing Research Facility (AMRF).[1]

Section 2 briefly describes the function, rationale and design philosophy of the AMRF. Section 3 discusses the principles employed in the design of the control structure. Section 4 provides the functional descriptions of the control levels within the AMRF hierarchy. Section 5 includes a discussion of the techniques used to implement the present version of these systems. Section 6 reports on the expected evolution of control module implementations. Section 7 briefly describes the data management and communications systems and Section 8 contains a summary.

The AMRF

Background. The National Bureau of Standards has a fundamental commitment to promote the development of standards for automated manufacturing systems and to transfer technology to American industry. To meet this responsibility, the Center for Manufacturing Engineering at NBS has established an experimental test bed, the Automated Manufacturing Research Facility (AMRF). Basic principles from physics, computer science, the behavioral sciences, control theory, operations research, and engineering disciplines are being used to develop a generic factory model and to propose solutions to system integration problems.

By 1986, the AMRF will contain several robot-tended machining workstations, a cleaning and deburring station, an inspection station, a material handling system, factory control software, database management systems, and the communications support necessary to transform these individual components into a fully integrated, small batch manufacturing system (see *Figure 1*). In order to address the integration and standardization problems faced by the private sector, commercially available hardware and software are being used, wherever possible, to construct this test bed. In addition, industry, academia, and other government agencies are playing an active role in the development effort through direct appropriations, equipment loans, and cooperative research programs.

Design Philosophy. To achieve its goal, the AMRF must exhibit a greater degree of flexibility and modularity than any currently available flexible manufacturing system. To demonstrate this flexibility, the AMRF incorporates commercially available manufacturing and computer hardware from many vendors. It is intended that additions, deletions, and substitutions of software and hardware modules may occur at all levels. To meet these requirements, the AMRF real-time production control system has been:

1. Partitioned into a hierarchy in which the control processes are isolated by function and communicate via standard interfaces.
2. Designed to respond in real-time to performance data derived from machines equipped with sensors.
3. Implemented in a distributed computer environment using recent advances in software

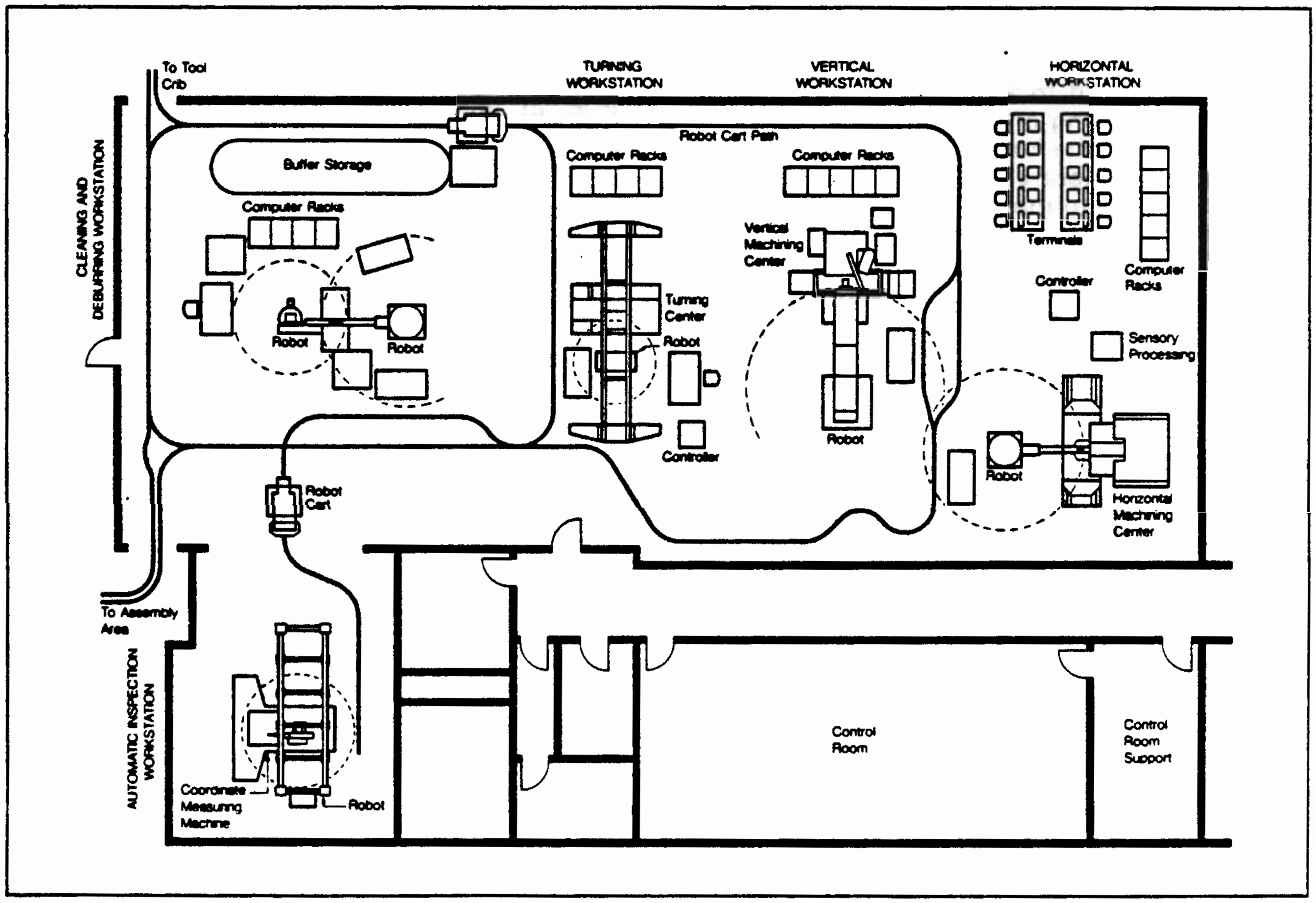

Figure 1
Automated Manufacturing Research Facility

engineering, microcomputers, and artificial intelligence programming techniques.

To support this real-time control system, it is necessary to design an information management service which not only provides for the storage and retrieval of various types of data, but also the timely and reliable transport of that data from one control process to another. A review of other approaches to controlling these types of systems can be found in Reference 2.

Principles of Hierarchical Control

As noted in the preceding section, the AMRF system architecture is based on the classic hierarchical, or tree-shaped, command/feedback control structure (see *Figure 2*) typical of many complex organizations.[3-7] This approach ensures that the size, functionality, and complexity of individual control modules is limited.

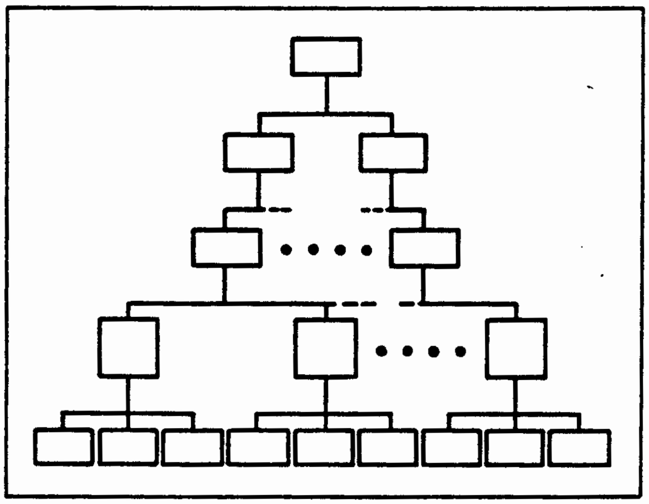

Figure 2
Typical Hierarchical Organizational Structure

Although the flow of control in this hierarchy is strictly vertical and between adjacent neighbors only, it is necessary and even desirable to share certain classes of data across one or more levels. The unique features of the AMRF hierarchy include: (1) the number and generic nature of the control levels (see *Figure 3*), (2) the amount of real-time computations, sensory processing and data transfer performed at each level, and (3) the strict adherence to the principle that modules be designed so that humans can comprehend and interact with them.

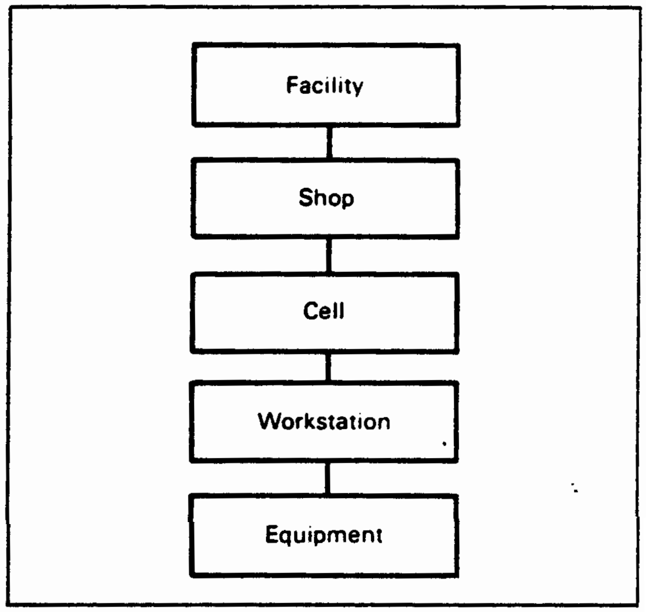

Figure 3
AMRF Control Levels

The amount of computations that must be carried out in real-time by a control module is limited by the planning horizon, i.e., the period of time over which the module is responsible for planning and updating local goals. These goals must be consistent with those set by the supervisor and commit the entire subordinate structure to a unified and coordinated course of action which, if successfully completed, would result in all goals being achieved.

To achieve these goals, each control module decomposes the current input command from its supervisor into procedures to be executed at that level, subcommands to be issued to one or more subordinate modules and status feedback sent back to the supervisor (see *Figure 4*). This decomposition process is repeated until, at the lowest level, a sequence of coordinated primitive actions is generated which actuates shop floor equipment.[4-7] The status feedback that is provided to its supervisor by each subordinate is used to close the control loop and support adaptive behavior at each level of control.

Functional Requirements

An analysis of traditional small batch manufacturing systems provided the foundation for the construction of the five level control hierarchy[8,9]

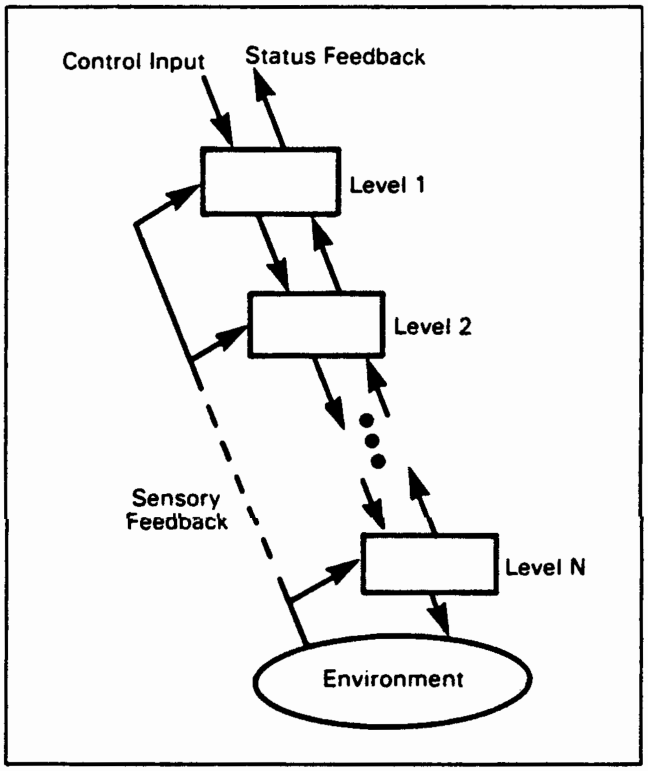

Figure 4
Control System Hierarchy

shown in *Figure 3*: *facility, shop, cell, workstation,* and *equipment*. Each of these levels is data-driven, and can be expanded to yield a more traditional tree-like hierarchy as depicted in *Figure 5*. This control structure provides a mechanism for partitioning the functions and databases needed to meet manufacturing requirements.

Facility Control System. This highest level of control implements the "front office" functions that are typically found in small batch manufacturing facilities. The planning horizon at this highest level can be anywhere from several months to several years. The level is broken down into subsystems that fall into three major functional areas: manufacturing engineering, information management, and production management.

Manufacturing engineering functions are typically carried out with human involvement via user data interfaces. One subsystem, computer aided design (CAD), is used to develop geometry specifications and bill of materials for assemblies, parts, tools, and fixtures. This information drives the process planning system which is used to prepare the specification of all operations necessary to transform a part from raw material into a finished product.

Information management provides user data interfaces to support necessary administrative or business management functions such as cost estimation, job cost accounting, customer billing, inventory accounting, customer order handling, procurements, personnel management, labor hours tracking, and payroll handling. AMRF research, for the most part, has not addressed these functions.

Production management tracks major projects, generates long range schedules, identifies production resource requirements, determines the need for additional capital investments to meet production goals, determines excess production capacity, and summarizes quality performance data.[8,10] Production planning data, in the form of long range schedules, is used to determine which production work orders will be released to the shop control system at the next lower level.

Shop Control System. This level is responsible for coordinating the production and support jobs on the shop floor.[8,10] This system is also responsible for the allocation of resources to those jobs. The shop control system has a planning horizon which can be anywhere from several weeks to several months. Two major component modules have been identified within shop control, i.e., a task manager and a resource manager. The first schedules job orders, equipment maintenance, and shop support services, such as housekeeping. The task manager also tracks equipment utilization and schedules preventive maintenance for all cutting tools, fixtures, robots, machine tools, and material transfer equipment in the factory. The latter allocates workstations, buffer storage areas, trays, tooling, and materials to cell level control systems for particular production jobs. The resource manager also monitors and updates levels for all raw stock, in-process, cutting tools, and replacement parts inventories necessary to run the factory.

The task manager of the shop control system is responsible for capacity planning, grouping orders into batches, activating and deactivating "virtual" cells, assigning and releasing batch jobs to those cells, allocating resources to cells, and tracking individual orders to completion. The task manager uses the group technology (GT) classification, a special code that describes the characteristics of each part type, to manage work flow. The volume of jobs that must be coordinated at the shop level demands that the controller must be capable of quickly making empirical decisions about individual jobs. GT codes are used to classify parts by processing requirements, geometric shape, tooling used, production costs, material composition, etc.

The shop control system coordinates the production and support activities that are carried out by the cell controllers at the next lower level. Cells are organized around GT part families or support functions. In the AMRF, GT cell controllers are designed to be production management specialists for particular part families. Instances of cells, referred to as virtual cells,[8] will be dynamically activated by shop control on the basis of production requirements. The shop deactivates virtual cells and removes them from the AMRF control structure when their assigned production jobs are completed.

The resource manager is responsible for allocating the production resources, as outlined above, to individual cells. This system is responsible for dynamically altering the organizational structure of the AMRF by assigning workstations, on an "as-needed" basis, to particular virtual cells. In order to make the resource manager self-regulating, an auctioning scheme is planned in which the resource manager would assign resources to the requesting cell with the highest bid. Cells would automatically compute bids on the basis of job priorities, due dates, cost estimates, and/or cost ceilings.

Cell Control System. This level of control is responsible for sequencing batch jobs of similar parts through workstations and supervising various other support services, such as material handling or calibration. The cell control system has a planning horizon which can be anywhere from several hours to several weeks. The cell brings some of the efficiency of a flow shop to small batch production by using a set of machine tools and shared job setups to produce a family of similar parts. The AMRF cells are virtual cells, dynamic production control structures which permit the time sharing of workstation level processing systems. The software structure was named the "virtual" cell to distinguish it from previous "real" manufacturing cells which are defined by fixed groupings of equipment or machinery on the shop floor. A detailed discussion of the

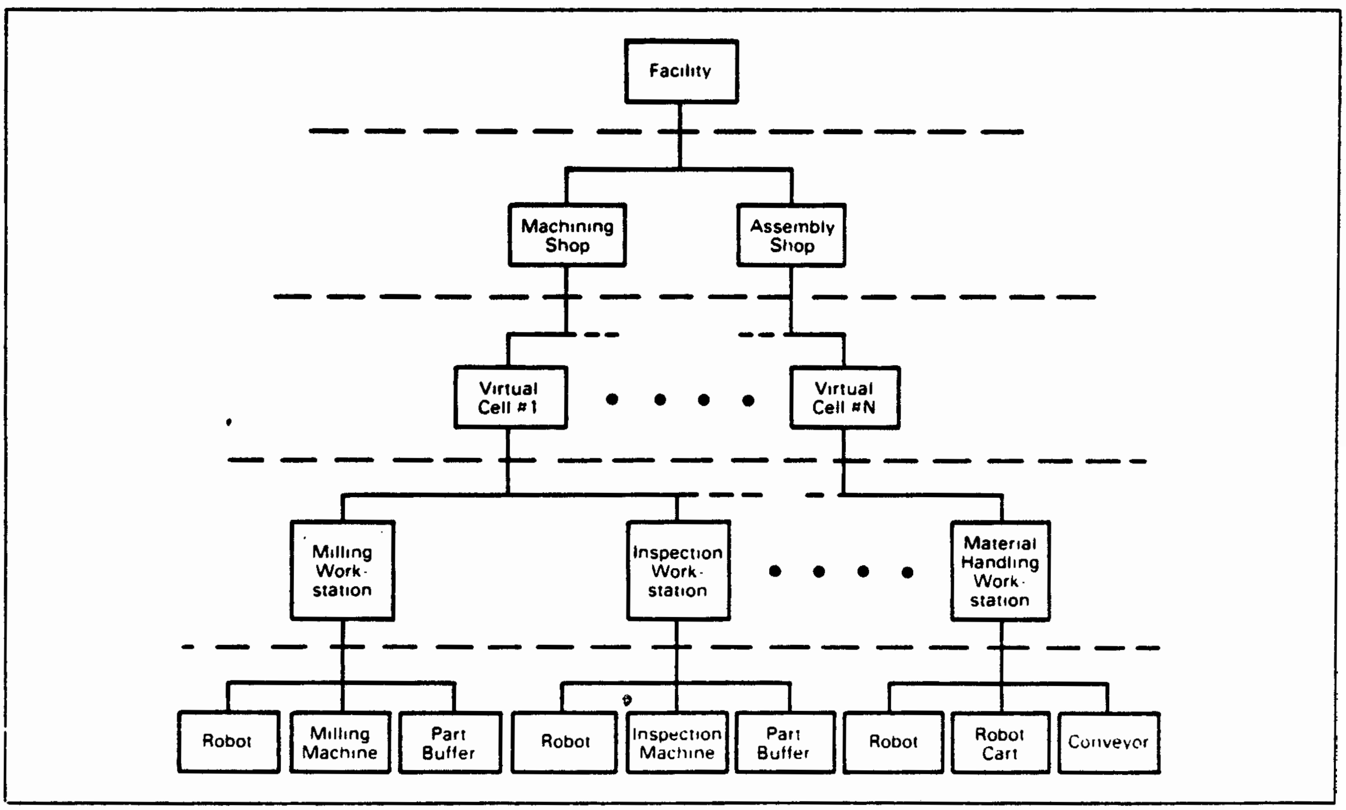

Figure 5
Expanded AMRF Control Hierarchy

virtual cell concept is found in Reference 8.

Modules within the cell control system perform task decomposition, analyze resource requirements and prepare requisitions, report job progress and system status to shop control, make dynamic batch routing decisions, schedule operations at assigned workstations, dispatch tasks to workstations, and monitor the progress of those tasks. The current internal structure of the cell is described in Reference 11. The cell level is the highest level of control that is currently operational within the AMRF (see *Figure 6*).

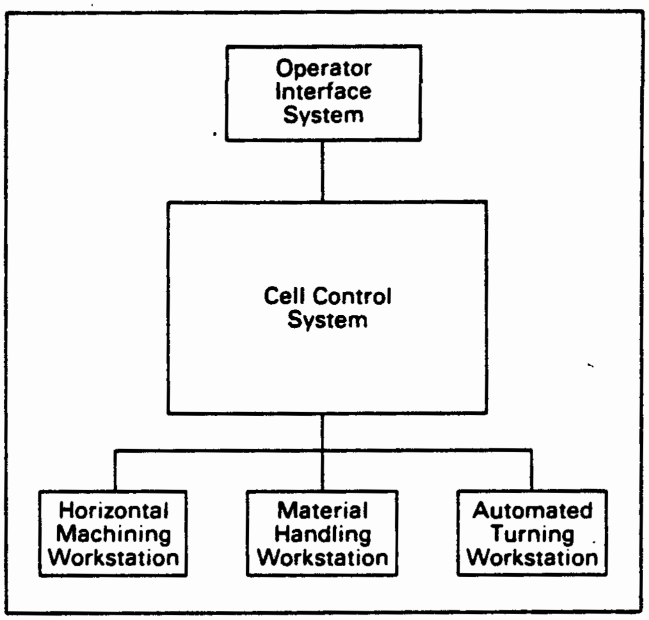

Figure 6
Current AMRF Control Structure

Workstation Control System. The activities of small integrated physical groupings of shop floor equipment are directed and coordinated by this level of control. A workstation control system has a planning horizon which may be anywhere from several minutes to several hours. A typical AMRF workstation consists of a robot, a machine tool, a material storage buffer and a control computer. A presentation of the architecture of the AMRF horizontal machining workstation, as illustrated in *Figure 7*, appears in References 12 and 13.

Machining workstations process trays of parts that are delivered by the material handling system. The controller sequences equipment level subsystems through job setup, part fixturing, cutting processes, chip removal, in-process inspection, job takedown, and cleanup operations. The cell-to-workstation control interface is designed to be independent of the workstation type. A uniform interface is necessary to support the dynamic control structure changes arising from the need to share workstations among virtual cells.

Equipment Control System. These are "front-end" systems that are closely tied to commercial equipment or industrial machinery on the shop floor. Their planning horizon may be anywhere from several milliseconds to several minutes. Equipment controllers are required for robots, NC machine tools, coordinate measuring machines, delivery systems, and storage/retrieval devices. These controllers will be required for "off-the-shelf" equipment to provide extended functionality and compatibility with NBS control concepts, until higher level front-ends are incorporated by system vendors.

The equipment control system interfaces to a workstation control system above and directly to the vendor supplied controller on the hardware under its control. The functions of the equipment controller are to translate the commands from the workstation controller into a sequence of simple tasks that can be understood by the vendor supplied controller and to monitor the execution of those tasks via the various sensors attached to the hardware. This approach implies that it may be possible to partition any equipment control system into a high-level controller, which is hardware independent, to perform the command decomposition and a low-level controller, which is hardware dependent, to monitor task execution.

Implementation

Presently, the cell system is the highest level of control implemented within the AMRF (see *Figure 6*). The cell system receives orders for batches of parts from a manually tended computer terminal, called the operator interface, which acts as an interim shop control system. The cell coordinates the activities of three machining workstation control systems—horizontal (HWS), vertical (VWS), and turning (TWS)—and a material handling system (MHS). Each machining workstation manages four equipment level systems, i.e., a robot, a machine tool, fixturing devices, and local material storage area. The material handling system manages a robot cart, a storage and retrieval system, and a loading/unloading area that is tended by shop personnel.

Since the emphasis in this design has been on the functionality and modularity of individual control modules, there has been no attempt to enforce a uniform method of implementation within control modules. In fact, several techniques and programming languages have been utilized in the design of the existing control modules with the AMRF. The horizontal workstation control system and all of its subordinates are programmed in FORTH. The turning workstation control system and its subordinate controllers are programmed in PL/M. The cell control system and the material handling workstation are currently programmed in the hierarchical control system emulator (HCSE),[14] with FORTRAN subroutines.

The HCSE was developed in the PRAXIS language (similar to ADA) specifically to aid in the design development, and integration of state-table driven real-time control systems.[3-7] Currently, the systems implemented using the HCSE run on a VAX-11/780 computer. The vertical workstation controller is currently running in stand-alone mode on a SUN microcomputer system in a LISP-based version of the HCSE developed at NBS.

Evolution of Control Modules

As previously discussed, every control module within the AMRF hierarchy (see *Figure 5*) reacts to inputs in essentially the same way: input commands from its superior are decomposed, status feedback data from subordinates is processed, and new outputs in the form of commands and status are generated (see *Figure 8*).

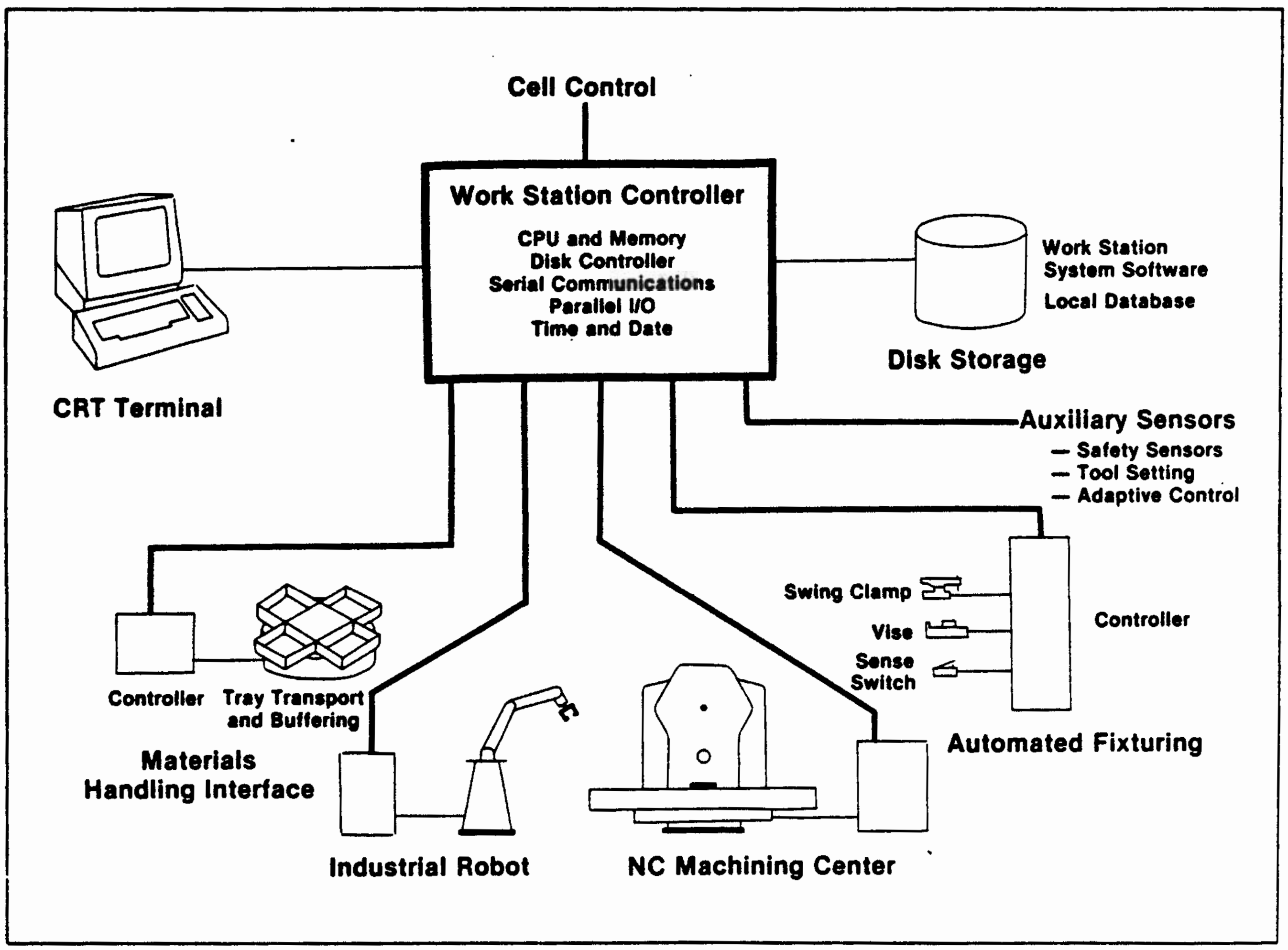

Figure 7
Workstation Control Architecture

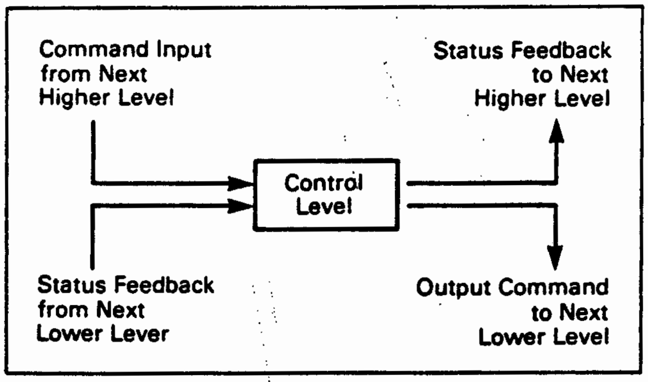

Figure 8
Generic Control Module

This mode of operation, referred to as reaction, represents the first of several levels of intelligent control. As the sophistication of control modules increases, at least four types of intelligence are envisioned: reaction, planning, optimization, and learning, as shown in *Figure 9*. A detailed discussion of the levels of intelligent control can be found in Reference 15.

The following sections provide a brief overview of the first implementations of two types of intelligence: a generic reaction-type execution structure called a production control module and a planning-type system which will determine the sequence of operations necessary to manufacture machined parts.

An Execution Structure for Control Modules. As indicated in earlier sections, any module in the AMRF hierarchical control structure may be expected to execute several functions in parallel to ensure that the jobs assigned by its supervisor are successfully completed. These functions are:

1. Decomposing complex tasks into simpler subtasks.
2. Assigning subtasks to appropriate subordinates.
3. Allocating required resources to subordinates.
4. Monitoring the execution of subtasks.
5. Updating schedules to reflect changes and delays.

All modules perform these same five tasks and each module at the same level performs a similar set of production and support activities.

An execution structure has been proposed[16] which can be incorporated into control modules at every level in the factory hierarchy. This structure partitions the aforementioned functions into three sublevels: production manager, queue manager, and dispatch manager. The production manager (PM) receives a list of jobs to perform and from this list creates a production plan. This plan contains the scheduling information for all the tasks required to complete each job and the subordinate responsible for completing each task.

There is one queue manager (QM) for each subordinate. Each QM is responsible for managing the queue of tasks assigned by the PM. There is also

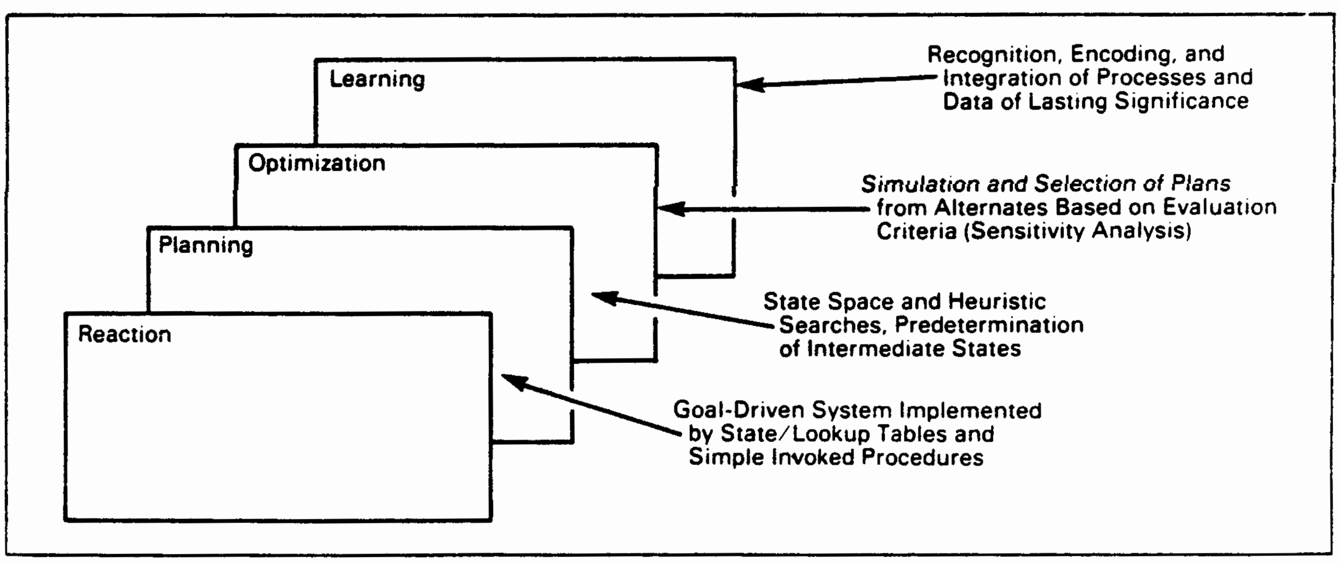

Figure 9
Evolution of an Intelligent Automated Control System

a dispatch manager (DM) which receives tasks from its QM and monitors the execution of those tasks by the corresponding subordinate. Each of these levels will be implemented using the state table approach discussed in References 3 through 7. In addition, a level independent interface format for jobs, commands, and status feedback has also been defined.

It is important to note that this represents the first attempt to separate data from control. Even though the data required to make "widgets" may be significantly different from the data required to make "gidgets", a uniform control architecture is possible which is independent of that data. This also implies uniform data structures for storing this data; those structures are provided by the process planning system.

The Process Planning System. As noted above, one source of input data required by the execution modules with reaction type intelligence is provided by the process planning system. In an automated environment, such as the AMRF, the process planning system must not only specify all of the machining activities required to produce a particular part, but also all robot handling sequences, feasible routings, fixturing, and raw materials. Furthermore, the system must provide this information in a manner which is consistent with the control architecture and with a uniform data format.

The current AMRF process planning system[17] is interactive and designed to provide planning data for control systems across the entire hierarchical factory structure. Furthermore, the process planning data package provides a uniform structure that is: (1) the same for execution modules at every level, and (2) compatible with the input requirements for the execution structure described in the preceding section. A process planning data package is comprised of three subsections: a summary header, a requirements list, and a procedure specification. Currently, the information contained in these packages is generated manually; in future versions it will be generated automatically by a distributed planning system.

In this distributed system, a specialized planning module will be associated with each controller. The planning functions will be carried out cooperatively across a distributed network of expert planning systems. A prototype expert module for planning machining operations has been developed and tested,[16] and work is continuing in this area.

Information Management System

The ability to manage the flow of information is an important ingredient in any effort to coordinate and control the activities in a complex organization. The system being developed to support the AMRF control hierarchy is divided into two subsystems which are described in the following sections.

The Data Administration System. The primary objective of the data administration system (DAS) is to provide a uniform method of access to data for all AMRF control modules.[10] The DAS system is composed of data dictionaries, commercial database management systems (DBMS), physical data storage devices, logical view processors, data manipulation language (DML) translators and interface software.

The operation of the data administration system is designed to be transparent to the application processes that it supports. Processes within the manufacturing facility post database queries and update transactions as messages in communications mailboxes. The transactions are written in a neutral, nonproprietary data manipulation language syntax. A local data administration system server, typically resident on the same computer as the application process, translates the transaction into the proprietary DML syntax of the commercial database management system in order to access the data. This approach allows control systems designers to build systems that are not tied to specific commercial DBMS implementations.

The initial database efforts focused on the development of a BCS/RIM-based centralized storage and retrieval system which supported a small set of predefined transactions for each control module. User queries and responses were transferred back and forth between remote systems and the centralized data administrator via the communications network. As the size and complexity of the data increases, this centralized system will be inadequate. Consequently, the final system architecture will be both physically and logically distributed with a standard query language for retrieving data. This system is called IMDAS (integrated manufacturing data administration system) and will support a variety of distributed data services. Complete details on the design and current level of implementation of this new system are contained in Reference 18.

The Network Communication System. The primary function of the network communication system is to provide the hardware and software required to transport information between AMRF process in a timely, reliable manner which is completely transparent to the control processes.[10] The system includes the transmission media, network interface units on individual computer systems, and software to packetize messages for transmission. Since control processes may or may not reside on the same computer system, it is necessary to develop a procedure for information transfer which is independent of the physical location of application processes and does not require direct physical connection of the origin/destination pairs.

In the AMRF, processes communicate with each other by writing and reading messages in memory areas that are accessible by both the process and the communications system. These "common" memory areas are called mailboxes. The communications system is responsible for delivering messages from the source mailboxes written by applications processes to any destination mailboxes that are logically connected to them. This mailbox scheme keeps the inner workings of the network transparent to the applications processes.

For those processes residing on the same computer system, communication typically occurs along common local data paths such as common memory. For those processes residing on different computer systems, an external network is required. The final architecture, illustrated in *Figure 10*, will contain a broadband factory network that support several subnetworks. The design will adhere to the standards set forth in the OSI reference model[19] and will employ protocols compatible with those being established for General Motors Corp.'s manufacturing automation protocol (MAP) system.

Concluding Remarks

The availability of sophisticated computers, robots, machine tools, and material storage and transport devices has generated interest in the development of techniques and standards that would facilitate the integration of equipment into flexible, automated manufacturing systems. The experience gained at the National Bureau of Standards from the Automated Manufacturing Research Facility demonstrates the absolute necessity of basing the design of such automated facilities on a sound, well structured model.

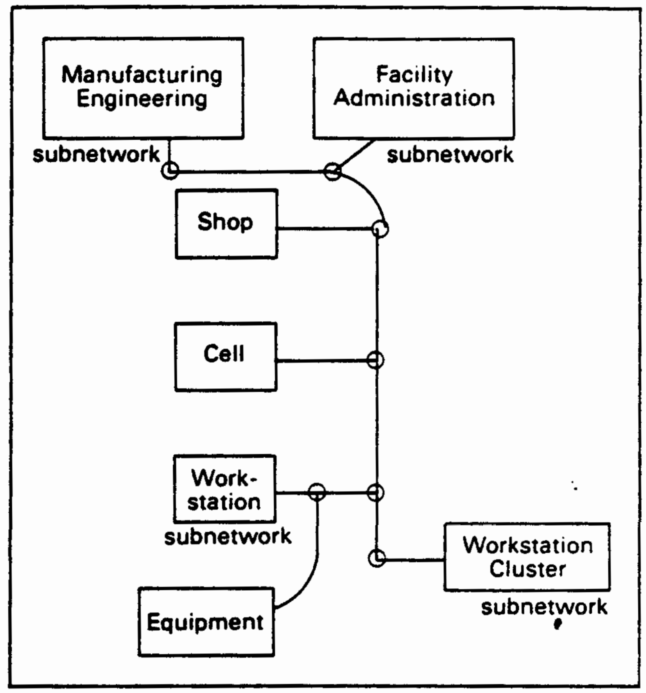

Figure 10
Factory Network Architecture

A standard factory model must address all of the necessary functional, control, data flow, and interface issues. Furthermore, the model should be based on fundamental scientific principles and be partitioned into submodules that can be readily understood by system developers. The hierarchical production control model described in this paper represents a first attempt to satisfy these requirements and to provide the foundation for generating a complete, generic model for the automated factory of the future.

Acknowledgement

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Charles R. McLean is a Computer Scientist and Group Leader of the Production Management Systems Group at the National Bureau of Standards. His group is responsible for the development of a number of AMRF planning and control systems, including, processing planning, cell, shop and the vertical workstation controller. He also has the responsibility of System Architect for the AMRF. He has authored and presented a number of papers of his work at NBS. Mr. McLean holds a Master of Science degree in Information Engineering from University of Illinois at Chicago, and a Bachelor of Arts degree from Cornell University. He is an active member of the SME, IEEE, and ASME professional societies. He was formerly an Electronics Officer in the United States Navy.