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HIERARCHICAL CONTROL AND REAL-TIME OPTIMIZATION IN AUTOMATED MANUFACTURING SYSTEMS

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

A major manufacturing research facility is being established at the National Bureau of Standards. The Automated Manufacturing Research Facility will address the standards and measurement needs for the factory of the future. A five-layer hierachical control architecture is under development to manage all production and support activities within the facility. The proper execution of many of these activities requires the solution to one or more optimization problems. This paper partitions these problems into levels consistent with the control architecture and reports on early work undertaken to solve some of them.

KEYWORDS:

Automated Manufacturing, Factory Model, Flexible Manufacturing, Hierarchical Control, Real-time, Optimization, Scheduling, Routing.

1. INTRODUCTION

In the past, manufacturing plants typically consisted of combinations of people and machines, working together to maximize corporate profits from the goods they produced. Because of poor planning and scheduling strategies, most of these plants were plagued by large work-in-process inventories, low utilization of equipment, insufficient throughput, and excessive delays, all of which decreased profits. Hopes for alleviating these problems were raised when automated equipment like industrial robots became commercially available and the sophisticated computer technology was developed to support it. Many companies made large capital investments in these new technologies expecting that their integration into existing plants would increase their profits and improve their shares of the world markets.

This has not happened, and the problems have not disappeared. In fact, their presence in these integrated, automated environments tends to have a greater negative impact. It is not possible to increase profits or achieve the desired rate of return on capital investments when expensive equipment is idle because of poor planning and scheduling.

This paper describes the approach under development at the National Bureau of Standards (NBS) to address these issues within the Automated Manufacturing Research Facility (AMRF) [1]. The remainder of this paper is composed of five sections. After this introductory section, section 2 provides an overview of the AMRF, including the design philosophy used in building it, its decomposition into basic, hierachically connected components, and a description of each of these components. In section 3, we identify the decision problems that exist in the AMRF, organized along the same lines as the hierarchical breakdown described in section 2. Section 4 includes a brief description of the efforts to date to solve some of these problems. Conclusions are given and future work is outlined in section 5. References are provided in section 6.

2. THE AMRF

2.1 Overview

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 [1,4]. Industry, academia, and other government agencies have played an active role in this development effort through direct appropriations, equipment loans, and cooperative research programs.

Physically, the AMRF contains several robot-tended machining workstations, a cleaning and deburring station, an inspection station, a material handling system, factory control software, database managememt systems, and the communications support to tie it all together. Basic principles from physics, computer science, the behaviorial sciences, control theory, operations research, and engineering disciplines have been used to transform these individual components into a fully integrated, flexible, small batch manufacturing sytem.

2.2 Design Philosophy

The AMRF is intended to exhibit a greater degree of flexibility and modularity than any currently available "flexible manufacturing system". To achieve these goals, the AMRF has adopted the following design philosophies concerning its control architecture. It is:

- o partitioned into a functional hierarchy in which the control processes are completely data driven and communicate via NBS-developed hardware and software interfaces which are uniform throughout the AMRF,
- o designed to respond in real-time to performance data obtained from machines equipped with sensors,
- o implemented in a distributed computer environment using state-of-the-art techniques in software engineering and artificial intelligence.

As noted above, the AMRF control architecture is based on the classic hierarchical, or tree-shaped, command/feedback control structure (see Figure 1) typical of many complex organizations [2-5]. This approach ensures that the size, functionality, and complexity of individual control modules is limited. 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. In addition, each control level is completely data-driven. That is, the data required to perform its functions is separated from the actual control code. All data is managed by a distributed.data administration system [26] and transmitted to and from control processes via a communication network that conforms to the Manufacturing Automation Protocols (MAP) [27].

2.3 Functional Decomposition

An analysis [1,4] of traditional small batch manufacturing systems provided the foundation for the decomposition of the control functions into five levels: facility, shop, cell, workstation, and equipment. Activity at each of these levels is data-driven, and each can be expanded to yield a more traditional, tree-like hierarchy as depicted in Figure 1. This structure provides a convenient mechanism for describing the functions of the automated facility and the databases needed to meet manufacturing requirements. This discussion is given next.

2.3.1 Facility Level

At this highest level are implemented the "front office" functions that are typically found in small batch manufacturing facilities. Activities at this level are grouped 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. This includes computer-aided design (CAD), Group Technology Classification, and process planning. The information management activities provide user-data interfaces to support

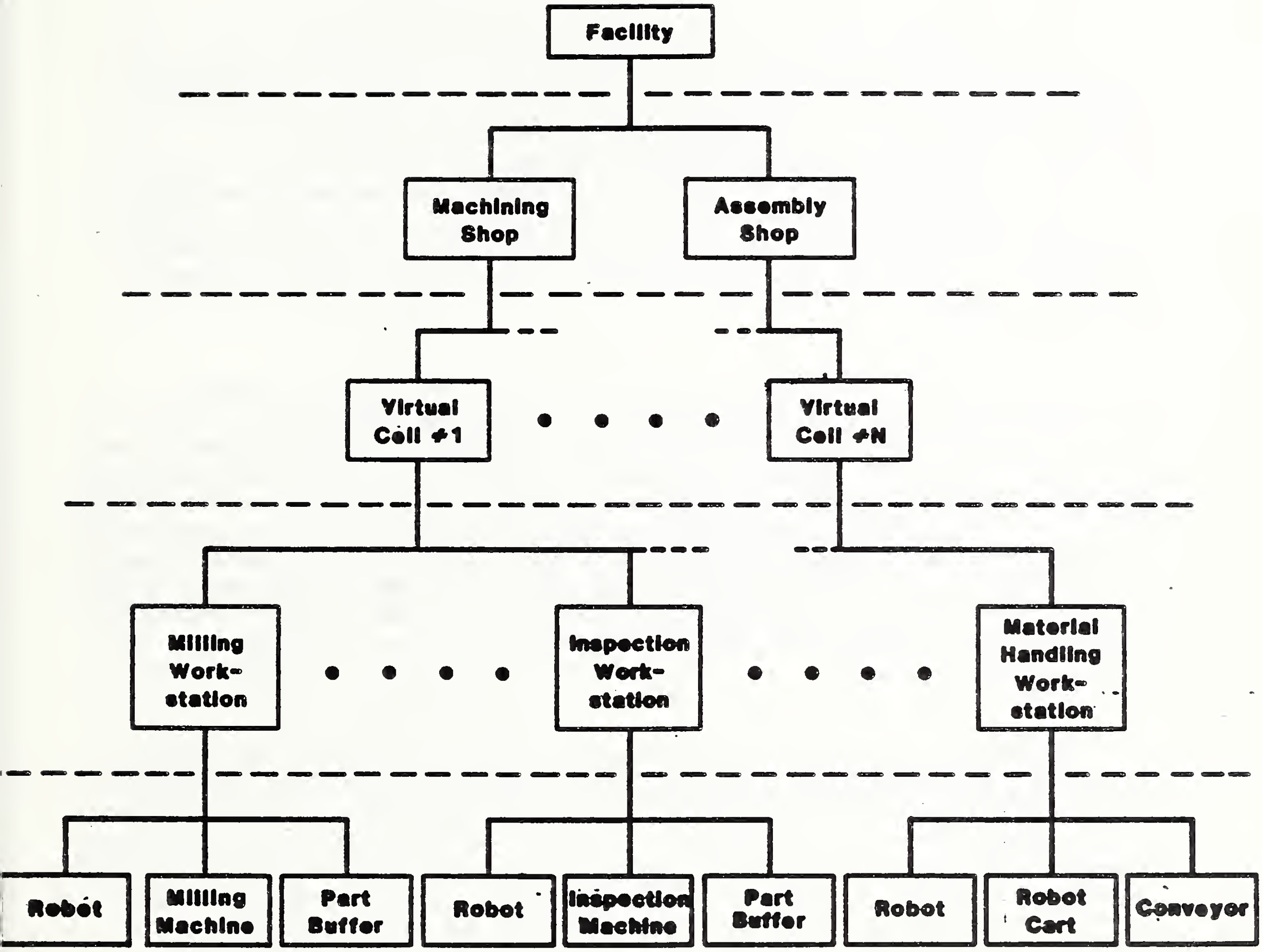

Figure 1. Expanded AMRF Control Hierarchy

necessary administrative or business management 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 [2,8].

2.3.2 Shop Level

This level is responsible for coordinating the production and support jobs on the shop floor [2,8]. It is also responsible for the allocation of resources to those jobs. Two major component modules have been identified within shop control: a task manager and a resource manager.

The task manager of the shop level system is responsible for capacity planning, grouping orders into batches, assigning and releasing batch jobs to cells, and tracking individual orders to completion. The resource manager is responsible for allocating the production resources to individual cells, managing the repair of existing resources, and ordering new resources.

2.3.3 Cell level

At this level, batch jobs of similar parts are sequenced through workstations and supervision is provided for various other support services, such as material handling and calibration. The cell [7] 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 dynamic production control structures which permit the time sharing of workstation level processing systems. This 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 virtual cell concept is found in [6].

2.3.4 Workstation Level

The activities of small integrated physical groupings of shop floor equipment are directed and coordinated at the workstation level [2,8]. A typical AMRF workstation consists of a robot, a machine tool, a material storage buffer and a control computer. 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.

2.3.5 Equipment Level

These "front-end" systems are closely tied to industrial machinery on the shop floor. Equipment controllers [2,8] are required for robots, NC machine tools, coordinate measuring machines, delivery systems, and storage/retrieval devices. The functions of the equipment controller are to translate 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 these tasks via sensors attached to the hardware. 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.

This paper expands the control hierarchy described above into a goal-directed one in which both planning and control functions are carried out at every level. The amount of computation that can be performed in real-time at each level is limited by the planning horizon: 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 module's supervisor and they must commit the entire subordinate structure to a unified and coordinated course of action. This course of action, if successfully completed, should result in all goals being achieved. In pursuit of these goals, each module decomposes the input commands from its supervisor into procedures to be executed at that level and subcommands to be issued to one or more subordinate modules (see Figure 2). This decomposition process is repeated until, at the lowest level, a sequence of coordinated primitive actions is generated which actuates shop floor equipment [10]. The status feedback provided to supervisors by their subordinates is used to close the control loop and support adaptive, real-time, decision making at each level.

3. REAL-TIME DECISION PROBLEMS

In this section, we identify the real-time decision problems that exist in the AMRF, which we believe are representative of those to be found in any automated manufacturing facility. The discussion is organized according to the five-level hierarchy of manufacturing system functions described above. What follows is, in a sense, a laundry list of problems, some classical and well-recognized, others new, arising from the introduction of new technologies into manufacturing systems. Indeed, some of the problems may seem insignificant now, but as automated systems become more sophisticated, the marginal gain from having optimal solutions to these problems could become extremely significant.

Since this is not a survey paper, no attempt is made here to provide a full review of the literature in these areas. For more information on the approaches, both classical and state-of-the-art, we direct the reader to some of the existing literature reviews [11-15], or to a recently published conference proceedings [16].

3.1 Equipment Level

The first level to be discussed is the equipment level, the lowest level in the hierarchy. The general rule for this level is that once a piece of equipment is instructed to do something, it must determine how best to perform it. The equipment on the shop floor is basically of two types: robots and machine tools served by the robots. In addition, we have separated the automated storage and retrieval system into a third category because of its special activities. All three catagories are discussed below.

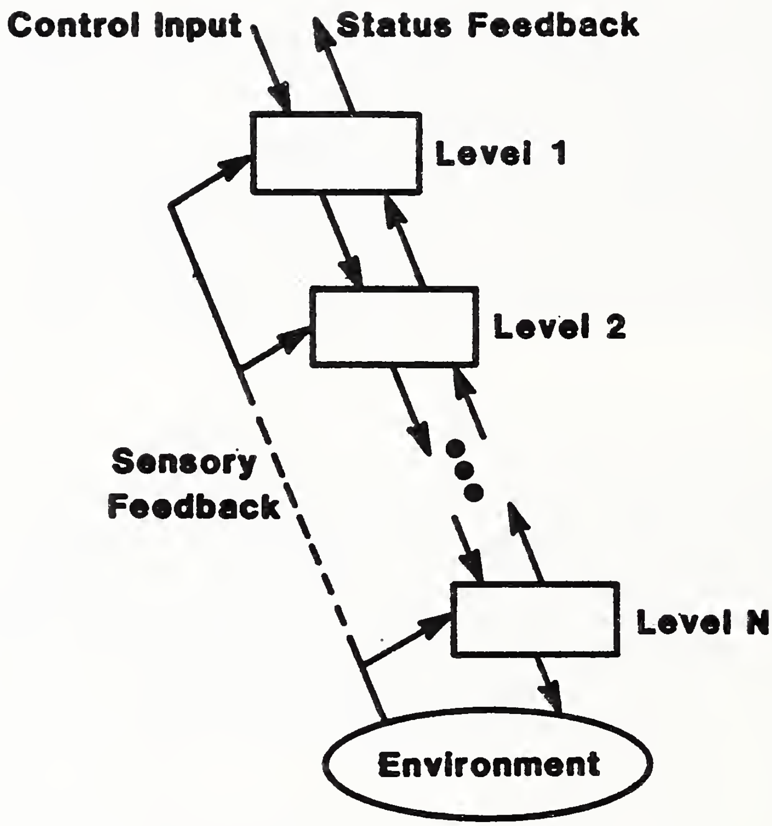

Figure 2: Goal-directed Hierarchy.

3.1.1 Robots

The mathematical decision problems to be addressed at the equipment level include path generation, optimal routing for traversing parts for inspection, sequencing of tasks or activities with priorities, and loading, unloading, and layout of parts and tool trays.

Sequencing prioritized activities is an area where much is already known. The literature is extensive on the single machine scheduling (sequencing) problem. In the automated manufacturing arena, the challenge is to do it in real time, and in such a way that the schedule can be changed when conditions change, without introducing too much nervousness in the system. There has been some work on this. See, e.g., [25].

The inspection robots and the cleaning and deburring robots both require paths to be generated for the movement of their arms and hands. These, of course, should be optimal paths; e.g., shortest, longest, fastest, or cheapest depending on the situation. In fact, in some cases optimality may not be appropriate and should be replaced with a sub- optimal, yet feasible and easily generated path. Obstacle avoidance techniques must be included in this effort also.

Another area where optimization methods can be brought to bear is in the loading, unloading and layout of trays of parts and tools. Portions of this are facility layout problems, thus some of the ideas from the facility layout and design literature could be useful. The problems can be complicated by the possibility that multiple geometries may exist in the same tray.

There is an interesting optimization problem concerned with finding optimal routes for traversing parts for inspection, cleaning, and deburring. The objective would be to perform these activities in a way that is optimal with respect to some measure, perhaps time, number of two-handed moves, or number of reconfigurations such as end-effector changes or part repositionings.

Another problem area is in the precise positioning of robot arms at the end of a path. This is an important problem and could be viewed as a solution to a nonlinear optimization problem in which the objective is to minimize the error in the actual position.

Pattern matching for robot vision systems is another area where significant optimization problems appear. These range from simple nonlinear least squares problems that arise from attempting to match patterns, to nonlinear least squares problems that arise in combining small windows of bit patterns to form larger windows for faster scanning.

The robot carts that serve the workstations must address some of the same problems as the fixed-position robots; they may, however, take on a slightly different look. For example, path calculations for the robots become routing problems for the carts. The issue here is deciding which path to take to deliver or pick up trays from the workstations. If the cart can travel forward and backward, the problem becomes more complicated. The situation is further complicated by having multiple carts, although the coordination activity for this is performed at the next higher level. The layout of the wire-guided path is also a task that lends itself to mathematical analysis and could be studied to determine the best paths to lay down.

3.1.2 Machine Tools

The decision problems that exist for machine tools are similar to those described above for robots. Perhaps principal among these is the scheduling of all activities and sub-activities that occur. Examples of these schedulable activities are tool changes, refixturings, chip removal, coolant spraying, and general houskeeping. The schedule should be optimal with respect to some performance measure, such as number of tool changes, number of refixturings, time in queue, or number of late tasks.

Also associated with the machine tool is the layout problem of determining the optimal placement of tools in the tool drum. An obvious application of optimization techniques related to this problem is minimizing the number of tools required for performing a given sequence of operations. Included here, too, is the problem of deciding which tools on hand should be kept for later jobs and which should be sent for storage elsewhere.

Just as in the case of the industrial robots above, tool path calculations are required for these machine tools. Lastly, there is the problem of developing diagnostics for tool wear and determining how and when to recover from errors.

3.1.3 Automated Storage and Retreival System

The automated storage and retrieval sytem has basically two decision problems that must be addressed. The first is determining optimal buffer sizes for all buffer storage areas. The second problem is concerned with the layout of the storage areas. In this latter case, the objective is to store all the parts and tools required for a given task together in one or more contiguous storage bins. Of course, this is difficult to accomplish since storage areas are required and released frequently, leaving available portions spread throughout the storage bin area. This is a problem in dynamic storage allocation and planning for storage needs. Its solution would have consequences for the time required to transfer these items to the workstation for processing.

3.2 Workstation Level

In general, most of the same kinds of problems that appear at the equipment level appear also at the workstation level, with the additional problem of coordination of sub-activities at the equipment level.

3.2.1 Material Handling

For the material handling workstation, the first priority task is to decide the sequence in which to perform the tasks assigned to it. In the case of multiple carts, decisions must be made about which cart to be assigned to which task. Then, an optimal routing for the cart(s) must be computed. Lastly, all these activities must be coordinated and monitored for possible changes and updates.

Also to be coordinated by this workstation is the storage and retrieval of equipment at the workstation and at the inventory workstation (warehouse). Planning is required here to minimize the number of stores and retrieves required to perform a task, while restricting the size of local buffers.

Tray layout for mixed and non-mixed geometries must be performed at this level, also. This problem could be complicated by having multiple batches of parts on one tray, each of which may have different geometries. A further complication is that deliveries to more than one workstation may be combined into one tray. It is not clear whether this latter problem can be resolved at the workstation level or must be passed up to the cell.

3.2.2 Quality Control Workstations

At these workstations, there is again the problem of sequencing tasks or activities. For the inspection workstation, this consists of determining which jobs to inspect and when, as well as which inspection activity to perform at which time. Once these have been determined, the decision about which probes to use to inspect must also be made. Then, after inspection has been completed, some parts will have to be scrapped and some will be candidates for rework. There are decision problems here that relate to the costs and benefits in each case. They must be resolved in light of due dates, priorities, and other existing jobs. Once these decisions are made, the rework parts must be put into a tray for further processing. There is a tray layout problem that must be solved. Again, some results from the facility layout literature may help here. It is also possible that an expert system may be useful in this process.

For the cleaning and deburring workstation, it is important to note that, since it consists of two robots, assigning tasks for it may very likely be non-trivial. It is possible that both robots will be required at the same time to perform one task, which is an additional complication.

As in the case of the other workstations, the quality control workstations are also responsible for coordinating activities of all subordinates.

3.2.3 Machining Workstations

At the machining workstation, the sequence of jobs to be done must be calculated, along with the coordination of activities of all subordinates. Conflicts of subordinate activity must be resolved, and if necessary, tasks reassigned. Assembly of parts may also be required at this level.

3.3 Cell Level

Basically, the cell must decide which workstation to use to perform a given operation. The problems at this level consist of scheduling tasks for the workstations in the cell, coordinating activities (parts and tool shipments) in supprot of that schedule, and coordinating delivery of parts and tools from one workstation to another. Coordination becomes a more crucial activity when there exist shared resources like material handling workstation carts. If there are, there is a serious problem in coordination that must resolved. Even if there are no shared resources, there is still the problem of multimachine scheduling that must be confronted. Conflict resolution is also a responsibility of the cell. When conflicts arise at the workstation level, the cell must replan, reroute, and reschedule to overcome them.

3.4 Shop Level

The shop level has overall responsibility for inventory control, tool management, scheduling, sequencing, conflict resolution, cell creation, and preventive maintenance for all equipment in the shop. Also developed at this level is the master production schedule and the material requirements plans.

The actual responsibilities in these areas will depend on the configuration of the shop; principally whether it contains any shared resources, which for the shop means whether there are any virtual cells. In this case everything below the shop level is a shared resource and the problems for the shop level controllers are more complicated.

3.5 Facility Level

The facility level has responsibility for the business and engineering functions which support the entire manufacturing plant. The mathematical techniques used in cost accounting, capital investment strategies, and many other business functions must be changed to include the impacts of automation [21]. In addition, new methods are needed to aid in the (GT) classification and coding of parts from CAD data, the geometric modeling of parts, the decomposition of complex geometries into features that can be machined and inspected, and the design, revision, and verification of process plans.

4. CURRENT WORK

In this section, we discuss some of the solution techinques under development at the AMRF.

4.1 Job Scheduling

The first project to be described is part of an ongoing cooperative research effort among staff of the Center for Applied Mathematics and the Center for Manufacturing Engineering of the NBS, along with researchers from various universities. The purpose of this long-term research effort is to identify and solve the real-time optimization problems found in the current and future configurations of the AMRF. The first part of this plan consists of a series of research efforts whose goal is to provide solutions to the multi-machine, multi-task scheduling problems at the cell level. The work described in [23] is part of the early phase of this research effort whose purpose was to ensure a basic scheduling/routing capability for the AMRF that was flexible and modular enough to allow incorporation of further results from other research and testing efforts being performed parri passu.

The report [23] documents the scheduler subsystem used in the June 1985 realization of the AMRF. This subsystem is responsible for managing the queues at each workstation and monitoring the completion of the tasks assigned there. The scheduling subsystem relies on data structures that use linked lists to track data so that a schedule can be created, modified, updated, and entirely deleted for each workstation. This subsystem also provides for the real-time switching of scheduling algorithms so that jobs can be expedited by the operator.

As mentioned above, the work reported in [23] provided a short-term solution to the scheduling problems in the AMRF and a foundation on which to build the longer-term solution. At the same time work was underway to develop these longer-term solutions.

A literature review [11] helped in determining the state-of-the-art in this area, and set the stage for the new results described in [25]. This paper investigates the dynamic scheduling of the Automatic Turning Station (now called the Turning Workstation.) The dynamic scheduling problem is treated as a series of static problems which are solved on a rolling-horizon basis. Characteristics of the optimal solutions to the static mean flow time and mean tardiness problems are developed and an implicit enumeration approach to the mean tardiness problem was also developed. These results are extended to drive dispatching procedures for the dynamic case.

A simulation model [24] was developed and used to evaluate the performance of these procedures relative to four other dispatching rules which are modifications of heuristic methods found to be effective for conventional single-machine problems. The modifications are necessitated by the need to incorporate job batching and changeover time. The results indicate that two new rules developed, the Modified Myopic rule and the Revised Necessary Condition-Based rule (based on the necessary conditions for local optimality of the static problem), work well under a broad range of experimental conditions. These rules are computationally efficient enough to operate on a microcomputer within the real-time constraints of an automated manufacturing facility.

4.2 Cart Scheduling

Materials are transferred between workstations within the AMRF on two Automatic Guided Vehicles (AGVs). Each AGV has two roller beds which means that it can transport two trays of materials simultaneously to any of the workstations. This transfer takes place over a wire which is taped to the floor. The actual path is shown in figure 3. The fact that it is not a loop simplifies the routing problems but enhances the possibility of collisions and deadlocks. This also complicates the scheduling problems.

A three-phase approach is under development at the AMRF to resolve these problems [17]. The first phase uses a simulation of the current state of the shop floor conditions to generate feasible schedules, using a predetermined set of strategies, for all proposed material transfers. The second uses a realization of the Petri net representation, shown in Figure 4, to eliminate those schedules resulting in collisions or deadlocks. The third phase will generate performance characteristics for each of the remaining feasible scehdules and select the "best" one.

4.3 Robot Path Planning

As noted above, obstacle avoidance and path planning are two of the most important optimization problems to be resolved in the control of robots. A path planning algorithm, which is guaranteed to be collision- free, has been developed at NBS [19]. Currrently, this algorithm assumes that the robot is the only moving object within the work volume and that this work space is modeled using an "oct-tree" representation [18]. The output from this algorithm is a piece-wise linear, collision-free, 3-D path from the initial to the goal state.

There are three major search techniques used to find this path. A hill climbing technique, with the Euclidean distance as its objective function, is used to reach a local minimum. The A* best-first search technique [22], with h heuristic equal to the Euclidean distance from the current point to the goal, is used to move away from this local minimun. These two techniques are combined, possibly many times, until the goal is reached. The resultant path is then checked, using a multi- resolution search, for collisions. This process is repeated until a satisfactory path has been found. This path is then passed to a trajectory planner where the velocity, acceleration, etc. required to move the robot are calculated.

5. CONCLUSIONS AND FUTURE WORK

Two major areas related to real-time production planning for automated manufacturing systems have been addressed in this paper. First, these planning problems have been identified and partitioned into five layers to match the control hierarchy under development for the Automated Manufacturing Research Facility at NBS. Second, a review of the recent efforts to solve some of these problems has been included.

Future research will focus on two major areas. First, work will continue on the integrated planning and control architecture proposed in [20]. That framework consists of a generic production control module which can be used at every level in the hierarchy, a process planning system and command/feedback structures to provide data to those modules, and a data management system to store, update, and transfer that data in a timely and accurate manner. Second, we will focus on the development of solution techniques for the decision problems described in the preceding sections. This research will be conducted in three concurrent phases. First, we must determine the information, both qualitative and quantitative, required to solve each problem. Next, we must find efficient structures for representing that information. Finally, we will attempt to marry techniques from Operations Research and Artificial Intelligence to solve each problem.

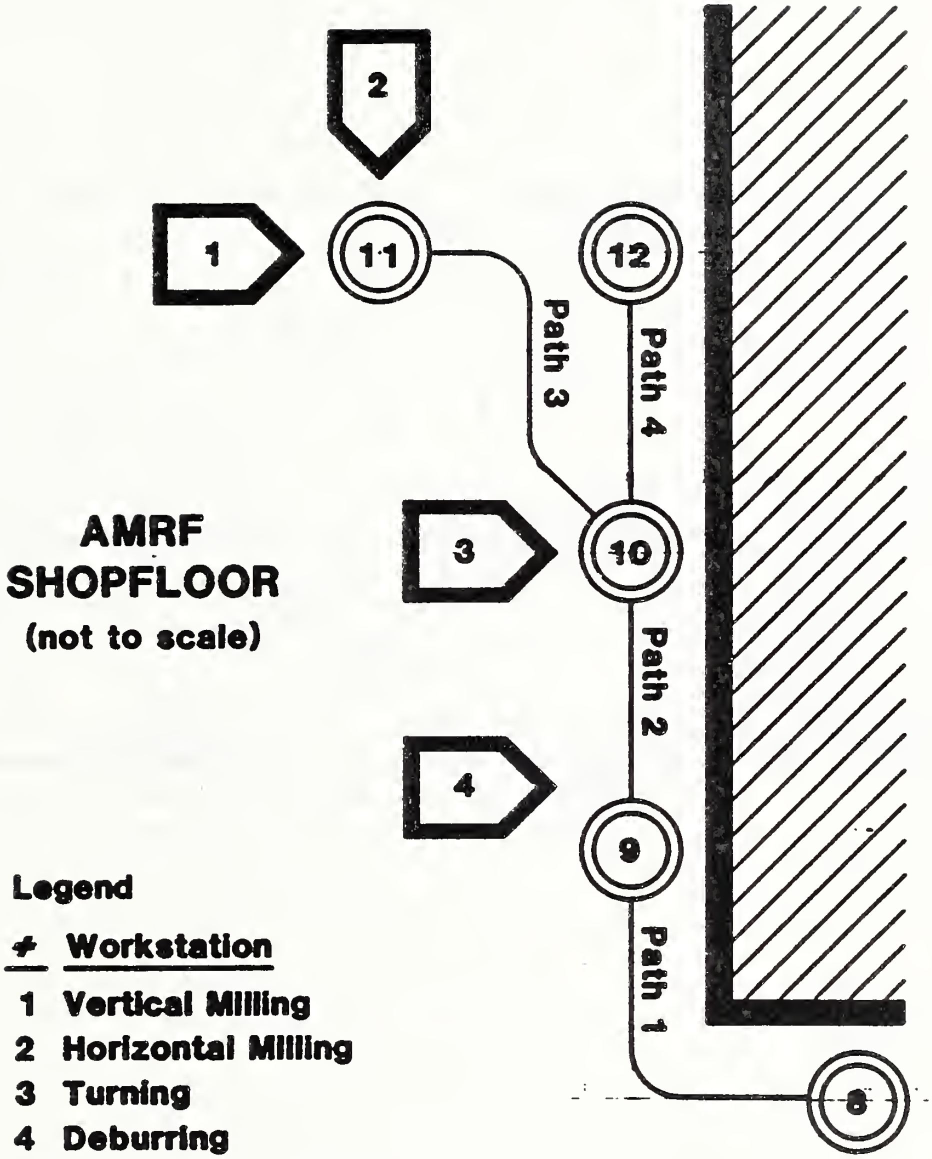

Figure 3. Wire-Guided Cart Path.

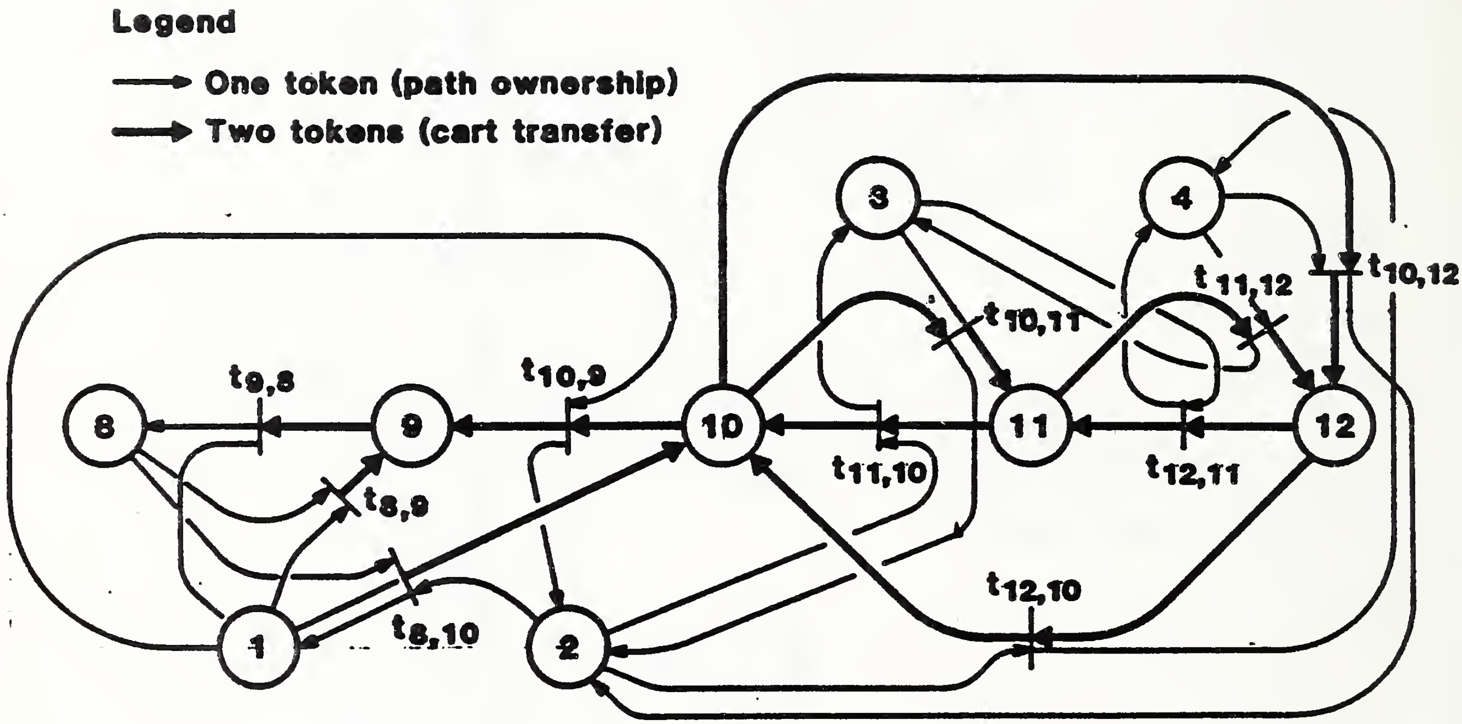

Figure 4. Petri Net Representation of Cart Path.

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

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

A major manufacturing research facility is being established at the National Bureau of Standards. The Automated Manufacturing Research Facility will address the standards and measurement needs for the factory of the future. A five-layer hierarchical control architecture is under development to manage all production and support activities within the facility. The proper execution of many of these activities requires the solution to one or more optimization problems. This paper partitions these problems into levels consistent with the control architecture and reports on early work undertaken to solve some of them.

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

Automated Manufacturing, Factory Model, Flexible Manufacturing, Hierarchical Control, Real-time, Optimization, Scheduling, Routing

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