# ADAPTATION OF FLEXIBLE MANUFACTURING CONCEPTS TO CONSTRUCTION

by

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## Introduction

This paper describes an exploratory investigation of the transferability of concepts developed for flexible manufacturing systems (FMS) to the control and automation of fixed plant types of construction processes. The overall goal is the application of structural analysis techniques, computer graphics, computer aided design and drafting, computer controlled machine tools, robotics, and artificial intelligence to the art of building with stone. The study is being conducted in conjunction with the Robot Systems Division of the National Bureau of Standards. Methods developed for the Automated Manufacturing Research Facility (AMRF) at NBS provide a starting point and conceptual framework within which the study will be developed.

## Study Objectives

The study has several objectives as follows:

(1) To become familiar with the problems of process control in automating construction operations.

(2) To establish the relevance of a hierarchical approach to system control of automated construction operations.

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(3) To gain a better understanding of the uses of sensors for data acquisition and machine control.

(4) To develop a framework for construction process control systems providing production control and process planning.

(5) To gain a better understanding of the data structures needed to support automation of certain construction operations.

(6) To better understand the concepts of the job cell and work station as they relate to construction process automation.

(7) To develop basic concepts regarding the system hardware integration required to automate construction operations.

In order to have a practical framework within which to consider these objectives, the stone cutting process is being used as a context for the study. It is hoped that by studying the hardware requirements (e.g. sensors, tool requirements, work piece stabilization and movement, etc.) for this process and developing control systems to implement process and machine control, generic conceptys for the automation of other construction processes can be developed.

## Existing State of the Art of Flexible Manufacturing Systems

The industrial and manufacturing sectors are experiencing a new wave of innovation. The concept of a flexible factory which can be quickly reconfigured to provide a variety of fabricated items is the focus of a great deal of research. Facilities which implement this concept are referred to as flexible manufacturing systems (FMS).

"An FMS basically consists of a collection of numerical control (NC) tools connected by an automatic material handling system. It operates as an integrated system under the direction and control of an on-line computer. The FMS is capable of processing a variety of part types simultaneously in random order and different part volumes; this inherent feature of the FMS makes it specially suited for batch manufacturing activities." (Cheng, Simulation, December 1985).

One of the major research activities investigating standards and guidelines for the operation of these facilities is located at the National Bureau of Standards in Gaithersburg, Maryland. The research facility at NBS is called the Automated Manufacturing Research Facility (AMRF). The research objectives of this facility are the development of manufacturing planning and control software and the development of protocols for system hardware integration.

The AMRF is configured into seven stations or systems. The seven production elements are the:

(1) Horizontal Machining Station
(2) Vertical Machining Station
(3) Turning Station
(4) Inspection Station
(5) Materials Inventory Station
(6) Transfer System
(7) Housekeeping System

According to an article describing the AMRF,

"The goal in designing the facility control architecture is to implement a system that provides sensory interaction along with the flexibility of software automation, i.e., the function of the system can be changed over a very wide range by varying data rather than by reconfiguring mechanical elements or reprogramming control structures." (Furlani, et. al., Vancouver, July 1983).

The AMRF research has led to a partial solution of the problem of converting part data in the form of a CAD image into machine control instructions. The solution utilizes two hierarchical data bases:

(1) The planning data base which contains part data and

(2) The control data base which contains management and system status information

The concept of "data driven automation" is implemented by information which is passed from one level to another. The data bases utilize task decomposition modules and feedback processors. These modules and processors control the flow of data through 5 hierarchical levels:

(a) Facility
(b) Shop
(c) Cell
(d) Work Station
(e) Equipment

Solution of the basic CAD/CAM interface and control problem has required the development of manufacturing planning and control software and system hardware integration control systems. The AMRF approach is limited to machining and does not address the difficulties involved in component assembly (e.g. welding). In addition, the stations have volume and weight restrictions.

## Adaption of FMS Concepts to Construction

A hierarchy of work division not dissimilar to that encountered in manufacturing exists in construction. One hierarchical breakdown is shown in Figure 1. Materials in construction flow from stockpiles and delivery points into the construction through a series of operations and processes which can be broken down into work tasks. Processes have characteristics similar to those defined as cells in manufacturing. Work tasks are construction "work stations." Moreover, batch types of production operations are not uncommon in construction.

| Hierarchical Level | Description and Basic Focus |
|---|---|
| Organizational | Company structure and business focus.<br>Head office and field functions.<br>Portfolio of projects.<br>Gross project attributes: total cost, duration, profit, cash flow, percent complete. |
| Project | Project definition, contract, drawings, specifications.<br>Product definition and breakdown into project activities.<br>Cost, time, and resource control focus. |
| Activity | Attainment of physical segment of project equated to time and cost control.<br>Current cost, time, resource use.<br>Status focus. |
| Operation | Construction method focus.<br>Means of achieving construction.<br>Complete itemized resource list.<br>Synthesis of work processes. |
| Process | Basic technological sequence focus.<br>Logical collection of work tasks.<br>Individual and mixed trade actions.<br>Recognizable portion of construction operation. |
| Work task | Fundamental field action and work unit focus.<br>Intrinsic knowledge and skill at crew member level.<br>Basis of work assignment to labor. |

Focus on project attributes and physical component items

Focus on field action and technological processes

Figure 1. Hierarchical Levels in Construction Management (Halpin/Woodhead)

Work tasks which require horizontally oriented operations can be related to the horizontal machining station of a flexible manufacturing system. Similar comparisons can be made between the other AMRF work stations and construction work tasks.

In contrast to manufacturing, decentralized work locations and on-site production activities are characteristic of construction. The distance between work stations and the weight of elements which are typically processed and handled in construction generate a set of problems which are unique. The nature of the construction production process often dictates that the equipment must be moved to the work element rather than work element moving to the equipment.

This notwithstanding, there are certain fabricated items in construction which are batch oriented and are processed with a fixed or semi-fixed plant. The production of concrete and asphalt are obvious examples. These are processes producing semi-fluid product. The pipe bending and reinforcement bending processes are piece oriented processes which have great similarity with the fixed work station concepts of FMS. Other piece or end item related processes which appear adaptable to the concepts of FMS are precasting operations, wood component fabrication (e.g. foof trusses, wall panels, etc.), stone cutting and building restoration.

Application of the FMS Concepts in Stone Cutting

Each of the stations constituting the AMRF at the National Bureau of Standards correspond to work tasks which are typical of the stone cutting process. Three of the elements of the AMRF have great similarity to stone cutting tasks and provide good vehicles for the study of FMS concepts applied to a batch oriented construction process. These are:

(1) The machining stations
(2) The inspection station and
(3) The transportation system

Each of these activities, as required for stone cutting, also reflect features which make construction automation unique in comparison to manufacturing automation (e.g. manipulation of heavy work elements, variation in the required dimensional tolerances, etc.).

Study of this rather simplistic fabrication process in construction can lead to the development of a framework for generating machine instructions from a CAD representation of the stone element to be produced. It is anticipated that many of the concepts developed to link the CAD image of a part with the machine instructions needed for fabrication in the AMRF will be adaptable to the stone cutting problem. The AMRF solution provides a starting point for study of the CAD/CAM interface for stone cutting. On the other hand, the stone cutting process introduces new problems which are uniquely characteristic of the construction environment.

Stone cutting has been selected for this study as a test vehicle specifically because of its relative simplicity and because some preliminary research on the machine level has been conducted. It does not require complicated assembly operations. The knowledge gained will relate to the flow of data and information to properly control this activity both at the process and machine level. It is anticipated that the principles developed will be applicable to other hierarchically structured batch processes encountered in construction.

The investigation will focus on the three stone cutting tasks noted above (e.g. machining or planing, inspection, and transportation). It will be assumed that the elements being worked are for column capitals and must be machined on four faces. This process is presently done by a mix of machine and manual methods and requires 16 working hours. The weight of these blocks is in the range of 1.5 to 2 tons.

## The Machining Task

In finishing a stone for use as an exterior facade panel, a window soffit, or a column capital, various types of saws and planers are used. The planer, in particular, has many similarities with the horizontal and vertical machining stations of the AMRF. The planer is used to shape the blocks and to give them a smooth finish. The height of the planer can be adjusted to fit the block being worked. Blocks are placed on a 12 foot bed and the planer can scrape away up to 3/4" of material across a 5 foot block width. The initial weight of a typical block is in excess of 5 tons. These blocks are then cut to smaller size when used for elements such as the column capitals.

The machining work is based primarily on hierarchical control. Although the complexity of the stone cutting operation is considerably less than that of manufacturing operations, it offers an excellent test vehicle for the study of hierarchical control in combination with FMS concepts in a construction environment. Study of automation of this kind of task/process will require consideration of problems such as weight, environmental control (e.g. dust abatement), part mix, part dimensions and geometry, desired grip points and tool requirements (e.g. cutter types and data control problems).

## The Transportation system

The weight of the material to be transported in construction processes such as stone cutting presents a special problem which is characteristic of the construction environment. In fixed construction plants (e.g. precasting facilities), a gantry type crane is commonly used to move heavy elements. Gantry cranes are also used in stone cutting plants. The methods of crane control vary, but in most cases skilled operators are required.

Control of the crane is closely related to the sequence of work tasks to be accomplished. Simulation methods are useful in determining what crane or other material handling activities will be required. Simulation can be used to script sequential activity both at the process (macro) planning and the work task (micro) planning level

According to Bonifioli, Garetti, and Pozetti, "simulation may provide suitable loading sequences for the FMS and for the single machines which are to be repeated cyclically."

(Bonifioli et. al. "Production Scheduling an Operational Control of Flexible Manufacturing Systems," Robotica, Volume 3, 1985).

Study of the stone cutting problem will focus on the control of crane operations as well as related materials handling devices (e.g. automated pedestals for turning and repositioning). The definition of data flow and data base requirements at both the macro and micro level will be studied.

Need for Process Production Control System

Process planning and production control is data driven at all of the AMRF levels. It is anticipated that a similar hierarchical structure can be used to control the stone cutting process. In order to achieve production control, planning must be carried out at all levels and the appropriate planning data generated and maintained. The functionally bounded modules defined in the NBS system constitute appropriate building blocks for the development of a real-time, adaptive, state-table driven, hierarchical production control system. The structured software developed to decompose task functions and initiate planning and control actions will be studied to determine its relevance to the stone cutting process control system.

Preliminary research is needed to identify and provide process planning functions that must be performed in an automated stone cutting facility. Further research will focus on an investigation of artificial intelligence and expert system techniques. The relevance of work already conducted for parts manufacture in this respect will be studied.

Data Base Considerations

As mentioned earlier, the AMRF is supported by two hierarchically integrated data base level involves strategic activities such as master production plans and schedules as well as engineering activities (i.e., design) and preparation of technological routes. The second level involves all short-range activities which are necessary for operative control of workstations and equipment. AMRF uses special purpose microcomputer-based systems to allow for a distributed processing environment and real-time control interface.

Data bases provide the central interface between:

a) Engineering and design with CAD
b) Technological sequencing of work tasks
c) Organizational sequences and schedules
d) Standard work task procedures
e) Monitoring and recordkeeping of operations
f) Automated inspection protocols

Elements a), b), c), and d) can be considered production planning oriented databases while e) and f) are required for process control.

Generally, automated fixed plant production systems in construction are comparable to manufacturing systems and can utilize similar data base structures. However, each data base system must be dynamically tailored to each process since processes vary significantly in complexity and require special features at the operational level. The necessary intelligence to support the operation of individual workstations has to be developed. Special attention in this investigation will be given to process specific data requirements. Even the simple stone-cutting operation requires extensive data support since control at the equipment level is still complex, involving sequencing problems as well as the handling of the different tools. Type and characteristics of the stone as well as the task requirements must be considered.

A multilevel data base structure provides the backbone for a flexible manufacturing system. The generic system developed by NBS provides a good foundation for the development of an automated construction process system. Simulation and emulation methods can assist in the design and testing of the database interfaces as well as the creation and modification of production oriented data bases (i.e., loading sequences).

## Microanalysis of Motions

Functions of robot control vary according to the complexity of the work task involved in the process. A complex work task is viewed by the robot control system as a group of primitive tasks which are to be processed in order to finish the complex task. Figure 2 shows the relationship between these primitives and the corresponding level of robot sensory control.

The motions to be performed by a robot constitute a complex work task. High level vision sensors reduce complex tasks to a set of simple ones. These in turn are further broken down into elemental

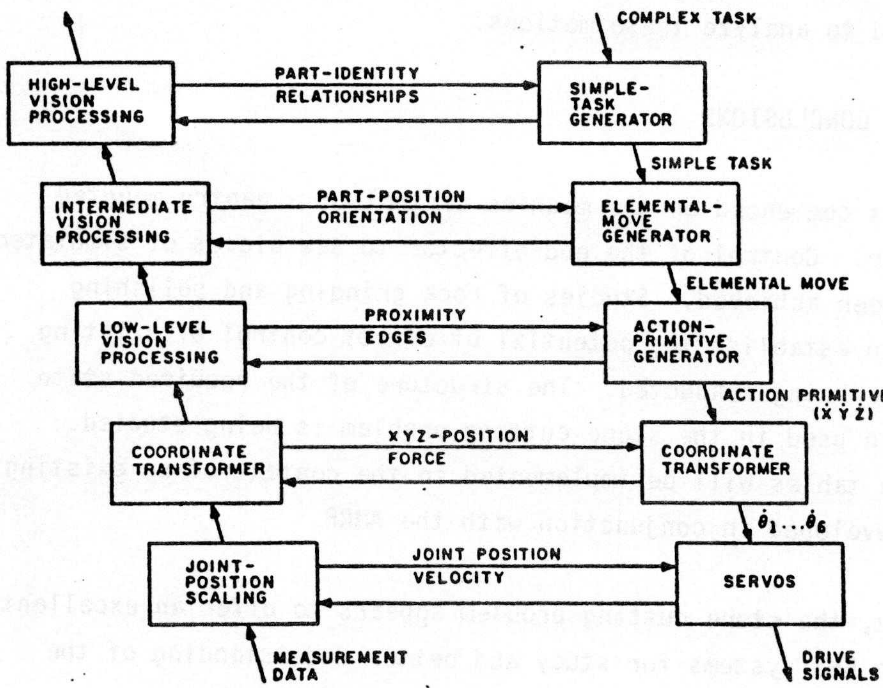


Figure 2. Relationship Between Primitive and Robot Control (Albus, 1981)

moves by intermediate vision processing. Elemental moves are the movements required by the different parts of the robot to process a given task.

These elemental moves are at a level subordinate to the work task as defined in Halpin and Woodhead (see Figure 1). Methods-time measurement (MTM) concepts and other micromovement analysis techniques must be used to analyze these motions.

SUMMARY AND CONCLUSIONS

Work has commenced on the machine control of a gantry mounted end-effector. Control of the end-effector to saw pieces of simulated stone has been achieved. Studies of rock grinding and polishing equipment to establish the potential of direct control of existing machines are being conducted. The structure of the required state tables to be used in the stone cutting problem is being studied. These state tables will be implemented in the context of an existing emulator developed in conjunction with the AMRF.

To date, the stone cutting problem appears to offer an excellent parallel to FMS systems for study and better understanding of the adaptability of these concepts to the construction industry.

## REFERENCES


Albus, J. S., Brains, Behavior, and Robotics, BYTE/McGRAW-HILL, 1981.

Bonfioli, M., M. Garetti and A. Pozzetti, "Production Scheduling and Operational Control of Flexible Manufacturing Systems," Robotica (1985) Volume 3, pp. 233-243.

Cheng, T. C. E., "Simulation of Flexible Manufacturing Systems," Simulation, December 1985, pp. 299-302.

Furlani, C. M., Earnest W. Kent, Howard M. Bloom, and Charles R. McLean, "The Automation Manufacturing Research Facility of the National Bureau of Standards," Paper presented at the Summer Computer Simulation Conference, Vancouver, BC, Canada, July 11-13, 1983.

Halpin, D. W. and R. W. Woodhead, Design of Construction and Process Operations, John Wiley and Sons, 1976.