FLEXIBLE CONSTRUCTION SYSTEMS (FCS)

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ABSTRACT

The need to increase safety, productivity, quality and efficiency in construction is a challenge to researchers to seek and develop bold innovative changes. Technological adaptation of successful concepts from other industries into construction offer an important path for innovative progress. This paper will provide an insight into some aspects of Flexible Manufacturing Systems (FMS) a concept developed by the manufacturing industry. The study of FMS shows that many of its relevant features, such as the concepts for automated process planning production control, and materials handling, are transferable into construction. If one is willing to accept the fact that many of the construction operations are repetitive in nature, requiring only limited flexibility of the production unit(s), a wide range of construction tasks are ready to be automated. It is a reasonable assumption that many fallacies can be avoided by learning from experiences gained in developing FMS for manufacturing. This approach was taken for developing concepts for Flexible Construction Systems which include all fixed or semifixed production operations found in construction. The objective of this paper is to introduce some basic issues related to integrated materials handling and production control and how they were applied in developing an automated truss production facility.

1. Introduction

The construction industry is currently poised on the threshold of a technological opportunity reminiscent of that experienced in the late 19th century. At that time new production methods, which promised great economical advantages, were developed. Scientific management techniques were created enabling the systematic analysis of production processes. Frederic Taylor (1856-1915) started to experiment with shovels of different sizes for different materials to find the best way to shoveling coal. Gilbreth (1886-1924) brought Taylor's ideas into construction. He focused his attention on the organization of the construction site. He pioneered rationalisation on the construction site by analyzing construction processes as systems. The results of his studies were used first within his own construction company but later published as a book called Field System. "Gilbreth's books were the first which emphasized the methods and the organization all the way down to the movements of hands."[6] Besides the introduction of motion studies, Gilbreth also developed "high-tech" concrete mixers to increase the productivity of concrete production. Gilbreth left the construction industry after his pioneering work.

Despite Gilbreth's early efforts, the construction industry has failed to sustain the big innovative advancements achieved by other industries. The reasons for this include the fragmentary nature of this business and the lack of emphasis on and funding for research and development efforts. Some construction companies, notably those overseas, have recognized this technological shortcomings and have begun to adapt FMS innovations for application to construction. In fact, these companies foresee the transformation of construction operations from a labor intensive, seat of the pants type process, into an automated environment more akin to a sophisticated manufacturing plant. Whittaker, emphasizes that :"Construction is a ripe, virtually untouched, and inevitable arena for robotic applications. Representing six to ten percent of the Gross National Product, construction dwarfs manufacturing and other industries that have successfully embraced simpler deterministic automation."[7] The economy of scale, safety problems, deteriorating quality and productivity rates, as well as an increasing gap of ongoing research efforts between the U.S. and other nations are factors which suggest that the U.S. needs to reevaluate its present state-of-the-art construction technology.

Automation is one concept which has had a significant effect on many industries. Robots, which are simply computer controlled automats, are a logical extension of the mechanically guided machines which were developed to mass produce standard items such as bottles or screws. The resistance of the industry as well as the scientists to acknowledge that construction includes repetitive, non-prototypical operations, contributed to the general ignorance of "high-tech" approaches. Today's (even yesterday's) generation of flexible, computer-controlled, and even intelligent machines are bound to nullify those arguments. Construction has a real chance to come of modern age by concentrating on opportunities rather than on limitations and superficial constraints. Construction has a tremendous opportunity to make a quantum leap in productivity, quality and safety by concentrating research and development efforts on developing applications for the use of these devices in the construction setting. The foundation, however, must be provided by scientific studies and a basic analysis of traditional construction missions and methods.

One approach to rapid technological advancements is the study of successful manufacturing systems to determine why they work and what the potentials are for technology transfer. This is the objective of a team consisting of researchers from the Construction Management and Mechanical Engineering Department at the University of Maryland. This group is funded through a grant from the National Science Foundation to study fixed and semifixed construction automation. The proposed approach is to develop a framework for the adaptation of the Flexible Manufacturing Systems (FMS) approach to construction. It is felt that FMS concepts can offer a great opportunity for the construction industry to benefit from lessons learned by adapting FMS principles to construction or modifying construction processes to enable the use of FMS.

2. Basic Characteristics of FMS and FCS

A FLEXIBLE MANUFACTURING SYSTEM (FMS) is a production facility consisting of flexible machines or work stations connected by an automated material handling system, all under the control of one or more computers. The characteristics of an FMS, outlined in Table 1, can be used as a basis for the study on how these concepts can be adaptated to construction.

In an FMS, quality control utilizes an automated measuring system, sometimes coupled with adaptive feedback. Today, quality control protocols in construction depend mainly on visual and tactile inspection, often performed with traditional instruments. The tolerances allowed for construction products are less stringent than those required in the manufacturing environment. However, the construction products being measured are rarely small in size, nor are they fixed rigidly as in manufacturing. In addition, the problems of a dusty, humid environment make the operation of sophisticated sensory devices difficult. These adverse conditions necessitate that certain FMS characteristics be modified for integration into existing construction processes, while some construction methods must also be redesigned to conform with FMS requirements.

To study the adaptation and integration of FMS concepts in construction, it is worthwhile to concentrate the research efforts on two major areas: flexible material handling, and computer process control through an automated production control system. The following sections address principles and ongoing laboratory research in each area and the results of applying some of the FMS principles to construction. Based on these findings, future research needs in the area of flexible construction automation will be outlined.

Table 1. -Principal Characteristics of FMS

FEATURE	DESCRIPTION	FEATURE	DESCRIPTION
MATERIAL HANDLING	* At the center of interconnected group of machines/tools * Use of conveyors	STORAGE REQUIRE-MENTS	* Just-in-Time Production * Automatic Storage and Retrieval Warehouses * Buffer Stores * Setting-up Area
PRODUCTION CONTROL	* Hierarchical Control System * Decomposition of high level goals into machine-executable instructions	MATERIALS HANDLED	* Typically Metal * Up to 760 cu.mm * Weight dependent on lifting equipment
QUALITY/ INSPECTION	* Automatic Measuring System * High levels of accuracy	ENVIRON-MENT	* Controlled humidity/ temperature * Need for swarf and chip removal
MANUAL LABOR	* Minimum labor needed for loading/unloading	SOFTWARE & COMPUTERS	* Highly Modular * Convertible
SUPERVISION	* Integrated * Coordinated between design and production	DATABASES	* Generally distributive * Real time requirements * Access Control and Security Demands
TOOLS & MACHINES	* CNC machines with monitors * Robots and carousels * Multiple Pallet Carriers	PROCESS PLANNING	* Variant Process Planning * Generative Process Planning * FCAD

A Flexible Construction System (FCS) can be defined as a fixed or semifixed production facility for construction where design, production planning, process control, and inspection are integrated. Today, many firms have implemented one or more of these functions independently, but with little thought to their integration. One of the essential elements of FCS is a well-designed, yet flexible data and information flow to bridge and extend the use of the distributed data bases. FCS can adapt some of the features of FMS in certain cases - for e.g., production control, automated material handling. In other cases, new techniques would have to be sought. Such areas include quality control and inspection, design of storage facilities. The lead that FCS has over traditional construction, especially in designing for construction, and automated rescheduling in times of resource and duration changes, is noteworthy.

3. Linking Processes through Integrated Materials Handling

Automated materials handling is the key link in the integration of "stand-alone" processes. Both the handling and the production processes can be considered independent subsystems of an overall production system. The material being worked on provides an interface between the various processes and its control is critical to the effective operation of the overall system.

The modeling of production operations as systems for the purpose of quantitative analysis has proven itself as a valid tool for analytical studies. The goal is to gain a "deep" understanding of the important relationships and the functions of the input factors affecting the efficiency and productivity of the operation modeled.

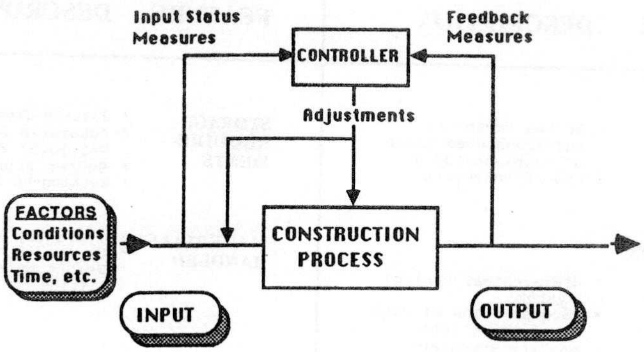

Figure 1. Model of the Self-Optimizing Production System

Figure 1 shows schematically how the major elements of a production process are related. Input factors, such as equipment or material, are needed to start the process, which produces an output, such as a concrete slab. Input status and feedback information provide the necessary measures for controlling the system by allowing for adjustment of either the input factors or the process itself. The control is based on monitoring the data flow, comparing it against expected values, and then planning and executing the adjustments. By linking processes, output of one process becomes input to another. In a simple case, the materials handling system moves material and provides it as a input factor to a production system. These production subsystems consist of resources specializing in a particular operation and are generally combined in independent workstation which can perform several functions or tasks such as drilling, deburring and inspecting. The more specialized the processes are and the greater the distance between their locations, the more complex is the materials handling effort. Figure 2 presents an overview of the four basic modeling elements needed for designing an integrated materials handling environment, i.e., machining/assembly workstations, material grasping and placing, movements, conveying mechanisms, and storage functions.

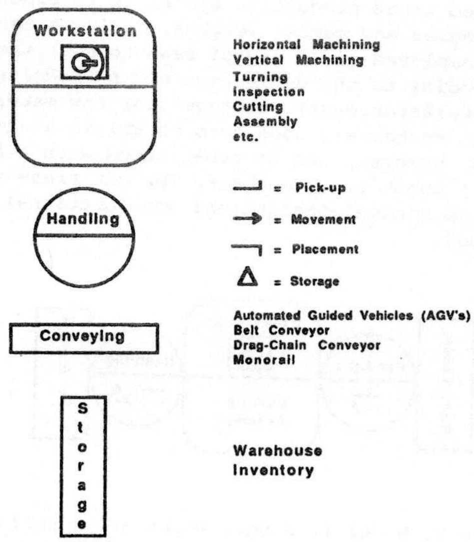

Figure 2. Basic Elements for Modeling Integrated Production Systems

This modeling nomenclature, developed by Mueller [5] distinguishes Manufacturing, Handling, Conveying and Storage as separate production systems. The above elements which are based on his approach, can be defined as follows:

- A **Workstation** represents a set of closely integrated machines and control systems which are designed to execute independently a certain family of related tasks.
- The **Handling** system includes all those functions which are needed to pick-up an element, move from x1,y1,z1 to x2,y2,z2, and place or store it in a designated area.
- The **Conveying** system consists of all the equipment required for carrying and taking components along a given path. "Individual conveyors, such as forklifts, diverless floor conveyors, and monorail overhead conveyors, correspond exactly to the vehicles; whilst continous conveyors, such as drag-chain conveyors or slat conveyors, come under the heading 'means of conveying'."[7]
- The function of a **Storage** is to maintain the condition of a stored object and to make it available at a determined point in time. Means of storage include standardized product carriers such as pallets and containers which are loaded and placed into and retrieved from laydown areas or warehousing facilities by automatic devices.

With these elements it is possible to construct operational models to describe the processes linked to a production system. The next section demonstrate how they can be used to model integrated truss production facilities.

3.1 Functional Concepts for Automated Truss Production

Since 1986 a small research team at the University of Maryland has developed concepts for automated truss manufacturing. Different systems were studied and analyzed using computer simulation [2]. Recently an actual "mini" facility has been completed.

The production of trusses entails two main operations, the cutting of truss members and the assembly into a completed truss. This requires the calculation of angles and length according to the engineers drawing. The cut members are then transported to an assembly area where different methods of assembly are utilized [1].

The objective of an automated truss production system is to produce trusses defined by geometrical features such as angles and member lengths. If it is assumed that the same production principles will be employed (i.e. use of saws to cut) the same two basic processes will be needed. According to the definition of the modeling elements, cutting and assembly can be assigned to a workstation(s). Storages for raw material and finished trusses as well as the handling system are needed to establish a simple production facility. The conveying system, however, can be substituted with a handling operation. The material to be handled are: (a) uncut truss members, (b) cut truss members, and (c) finished trusses. Based on these minimal operational and functional requirements, the following model can be developed.

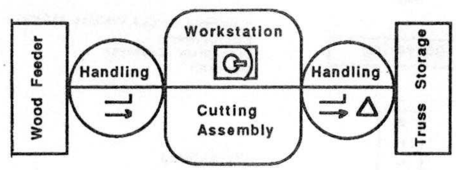

Figure 3. Model I, Single Workstation Facility

Model I has two storages, one for wood and one for trusses, two handling systems and one workstation which is able to cut the wood and assemble them to trusses. The symbols used in the modeling elements show that the first materials handling procedure involves the picking up of wood from a feeder and moving it to the workstation. After the truss is assembled, the trusses are picked up, moved to a truss storage area where they are stored ready for shipping to the construction sites.

A second concept is based on a separation of cutting and assembly into two workstations justified by their difference in operational objectives. If a conveyor system is needed to link the two (remote) workstations, a more complex model emerges.

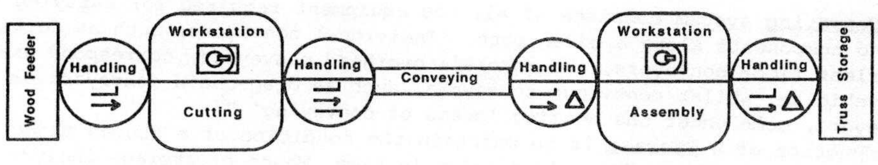

Figure 4. Model II, Multi Workstation Facility

Through the introduction of a second workstation, additional materials handling steps for loading and unloading the conveying system are required. The loading includes picking up, moving, and placing of the cut wood member onto the conveyor. After the element has arrived at its destination (i.e., at the assembly workstation), a handling device has to pick it from the conveyor and move it to the workstation for immediate assembly or storage in the work in progress (WIP) area.

Both models presented are possible configurations of effective systems. While Model I takes advantage of a reduction in handling activities outside the workstation, concept II favors a decentralized solution. The latter model might apply to a case where a company plans to automate an already existing facility.

4. Production Control Concepts

Automated production control is a second important feature of FMS. The following sections address some of the principles as they apply to truss production. The two major types of automated production facilities discussed above, the single workstation and the multi workstations concept, can be integrated to represent FMS which are intended to provide an integrated environment for computer controlled production. The control functions encompass various tasks such as planning and coordinating the different systems and production devices, monitoring and troubleshooting in case of an unforseen problem. Three basic control structures can be utilized: a) the centralized, b) the decentralized, and c) the oligarchical system. All three approaches can be build utilizing hierarchical principles.

4.1 Hierarchichal Control in Flexible Manufacturing Systems

Similar to the hierarchical levels existing in construction management, a control hierarchy, based on a tree-shaped command feedback control structure can be used for automated manufacturing. Based on the premise that overall goals can be broken into simpler goals, a hierarchy of goal oriented modules can be developed. "Each level is responsible for transforming an input goal into a set of simpler goals, and issuing these when approproприate to lower levels of control. When a control level accomplishes a goal, it reports this as status information to the next higher level; it then receives a new input that is the next step in accomplishing a higher level goal." [3] While the higher level control modules are dedicated to develop and monitor a general plan, the lowest levels are dedicated to a well defined task.

4.2 Centralized Control for a Multi Workstation Truss Production

In a fully centralized control system only one production controller interacts with all the elements involved in the production. This allows for direct execution of commands but requires that the central processor keep track of all the activities.

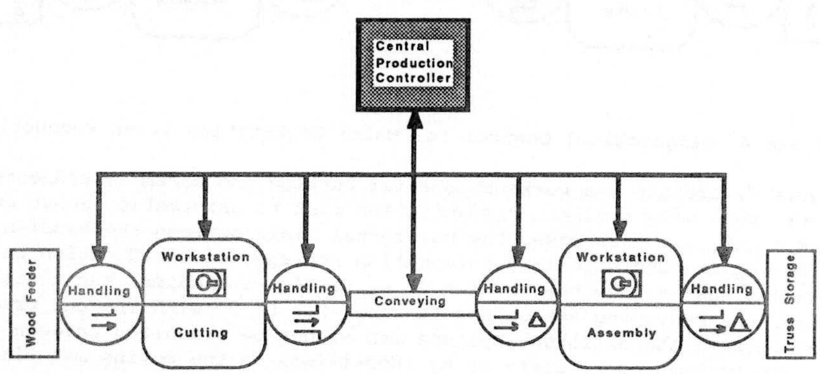

Figure 5. Centralized Control of Multi Workstation Truss Production

For the multi workstation truss production system a centralized production control would entail communcation links between every production device and the central processor. This however does not necessarily mean that the machines have to work in sequence. The use of a hierarchical control structure allows for parallel execution of tasks. Most of the time a full centralization is not possible, since robots generally depend on their own control systems which are able to execute and monitor standard commands.

4.3 Decentralized Control

In a fully decentralized control environment, each system entity is assigned a controller. To allow for interaction among entities, each controller includes a coordinator which allows it to communicate with all other controllers in the system. The main disadvantage of these systems is caused by the slow communication, which reduces the response efficiency between controllers. No major automated manufacturing system has decentralized control.

4.4 Oligarchical Control for a Multi Workstation Truss Production

The goal of the oligarchical control structure is to combine the advantages of centralized and decentralized control using the hierarchy as framework. In this scheme, communication does not solely follow the tree structure but allows also for horizontal links between control modules. Figure 6 presents a basic control scheme which is based on this apporach.

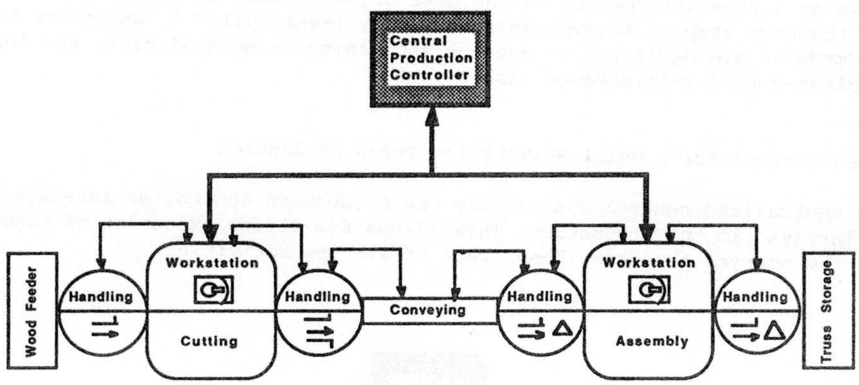

Figure 6. Oligarchical Control for Multi Workstation Truss Production

Shown in Figure 6, are the two workstations for cutting and assembly connected with the central processor. Both have a direct communication link to information about cut angles and layouts from a CAD or a data base. The horizontal links between the handling and the conveying systems require decentralized information storage for coordination purposes. For example, the handler has to know how to pick up a certain wood shape, and where to move and place it. In turn, the conveying system has to know what to do with the cut truss element. The "handshakes" between the different systems can either be organized through communication links between controllers or by identifiers on the moving material which can be interpreted by the different control systems. One possible technique is the use of barcodes and integrated barcode readers.

The last part of this paper presents a prototype single workstation truss production system. Hardware and software will be briefly described and observations made during the development of the system will be presented.

5. A Prototype Truss Production System

The Construction Automation Research Laboratory (CARL) at the University of Maryland was established late 1987 as an environment for the development of methods, related hardware and software to automate construction facilities. Some of these integrated elements include:

(1) CAD, (2) Artificial Intelligence, (3) Automated Process Planning,
(4) Production Control, (5) Sensors, (6) Data Bases,
(7) Communication systems with
(8) Robotics

The hardware was sponsored by an NSF Equipment Grant.

One of the initial projects is an automated truss manufacturing system which was designed to gain knowledge on how expert process planning systems can be developed, and integrated with robotics to create a flexible construction system. The wooden truss as a product was chosen due to its relative simplicity and the ease with which the wood medium could be worked on by the equipment available.

The hardware used in the development of the system includes one Mitsubishi Movemaster RM-501 robot arm, a 7.5 inch circular saw, a NEC Advanced Personal Computer IV with Ethernet connection. Figure 7 presents a schematic overview of the setup.

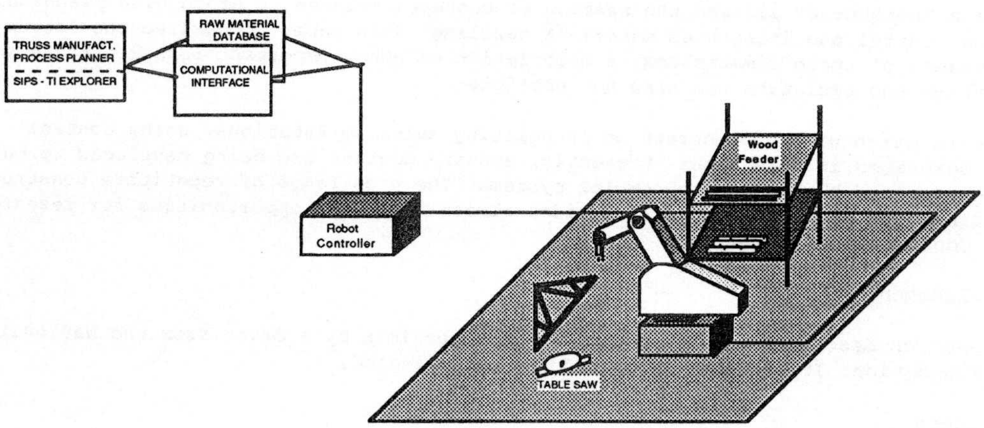

Figure 7. An Automated Truss Production System

Besides the wood feeder, software needed for planning and control had to be developed. First, a semi-intelligent Process Selector (SIPS) shell developed by Professor Nau at the University of Maryland was used to design a process planner which is able to analyze user-defined parameters to create a strategy on how to produce the designed truss. This process planner uses the knowledge bases of truss features and the processes required to produce these features. Second, an interface program which links SIPS with the robot controller had to be build. Thirdly, a raw material data base was developed to keeptrack of the material stock.

5.1 Experiences and Results

In March of 1988, the described system was able to cut and assemble automatically a truss design as shown in Figure 7 [4]. Several hurdles had to be overcome during the developmental work.

(1) The limited reach of the robot arm created significant constraints in terms of the possible size of the truss.
(2) A special feeder had to be designed and tested to supply raw wood members to the robot for automatic retrieval.
(3) A calibration scheme had to be developed for accurate handling and cutting of the wood members.
(4) Modifications on the hand were needed to allow for the assembly of the small truss members.
(5) A vacuum system had to be installed for actual cutting to avoid potential hardware damage with saw dust.

Since this was the first comprehensive system developed within CARL, many lessons had to be learned caused by the unfamiliarity with the mechanical limitations of the system. Many hours went into figuring out small problems and troubleshooting in an ocean of possible errors. However, the knowledge gained and the software developed during the project can now be utilized and expanded upon to create sophisticate systems with more complex applications.

6. Conclusion

The effort of adapting FMS concepts to construction shows first promising results. The experimental development of an automated truss production system using one single robot arm as the main "workhorse" allowed the testing of concepts related to production planning, production control and integrated materials handling. This paper emphasized the latter two areas. Because of space limitations, a description of other important research tools such as simulation and emulation was also not possible.

Future research will concentrate on integrating multi workstations, using control concepts described in this paper. Presently, sensory devices are being developed to build more decentralized but also more complex systems. The wide range of repetitive construction processes needing flexible controls provides almost limitless opportunities for research in Flexible Construction Systems.

7. Acknowledgment

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