DESIGN FOR AUTOMATED CONSTRUCTION

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ABSTRACT

When an existing product manufacturing process is automated, the largest savings are gained when consideration is given to modifying the design of the product and the components from which it is assembled. Traditionally, the manufacture of the product's individual components and its final appearance were the main factors in design. The final assembly of the product relied on the dexterity of the human for accomplishment. Humans have sensing, manipulative, and decision making capabilities that are far more versatile than the most sophisticated machine. When considering automation of a manual process, an important factor is to determine if the assembly operations are within the capabilities of the machine. The assembly of a product is often too complicated for automation and a redesign of the product is necessary to simplify the assembly process. The general rules by which this is accomplished are referred to as "design for automated assembly" techniques. The basic goal of these techniques is to simplify assembly so that the material feeding, manipulation, and assembly requirements are within the capabilities of the production system. This paper introduces this approach in the context of advanced technology and discusses a methodology to apply these principles in developing automated construction systems.

1. INTRODUCTION

The utilization of advanced automation technology in the manufacturing industry has greatly improved productivity over the past 20 years. Meanwhile, productivity in the construction industry has seen little, if any, improvement during that time. Application of advanced automation technologies in the construction industry has the potential for significant productivity increases. The application of advanced automation technologies in construction must analyze these technologies and their use in the manufacturing industry. The differentiating factors between manufacturing and construction must be identified. Existing applications of advanced technology in construction demonstrate trends and patterns that can be synthesized into concepts for applying automated manufacturing technologies in construction. The elements of an automated construction system can be configured and simulated on a computer. The use of this type of simulation tool allows investigation into the integration of a computer-aided-design (CAD) system as well as the potential utilization of artificial intelligence. Factors involving the economics of the simulated system can also be evaluated. The basic concept is to transfer current computer-aided-design/ computer-aided-manufacturing (CAD/CAM) systems into construction applications. This is a fundamental step in the necessity to evaluate the potential for improved productivity through utilization of advanced technology. Additionally, the results of this study may prove beneficial at a later date when the costs of advanced automation technology are further reduced, while their capabilities are improved.

2. PROJECT SUMMARY

Consideration of the production system must be coordinated with the product design when automated assembly is planned. This type of parallel planning is referred to as "integrated product development." The requirements of the assembly operation must be within the capabilities of the machines proposed to perform those operations. In consideration of the requirements for on-site building automation, a manipulative system capable of enclosing the floor, wall, ceiling, and roof systems within its work envelope must be available. This can be accomplished in one of two ways. The first is large scale manipulators such as cranes and lifting devices capable of moving the building elements into place. This approach lends itself to the assembly of large components which have been prefabricated. The second is to provide relocatable equipment which can be repositioned at various points in the work site. This equipment can be either special purpose hard automation or programmable, flexible equipment such as robots. The relocation capability can be either manual, semi-autonomous, or autonomous. Both the large scale manipulator approach and the special purpose machine approach involve large capital investments and, correspondingly, require a sizeable market for economic viability. An alternative approach is to spread the equipment costs over many construction operations. This system would utilize the ability of the robot to be reprogrammed to perform many different operations. Because many construction operations are beyond machine capabilities, modification for automation is necessary. The use of a single robot to perform many different operations allows the system to be modular. Additional robots might be utilized to increase production rates. In terms of reliablility, the malfunction of one robot would not adversely affect production since it is easily replaced by another.

The present trends in the robotics industry, the decreasing price of robots and their improving capabilities, would provide for economic payback of a flexible robotic construction system over a wider range of production volumes. Utilization of an on-site robotics system and the principles of designing for automated assembly in the development of integrated building systems requires one additional component. Available materials are not always in conformance with the requirements of the developed building systems. In order to process available materials and eliminate the need for off-site factory production facilities, it may be necessary to integrate a flexible work cell with the robotics system to process materials. After any required processing, the work cell could be fed materials manually and provide the materials for either manual or automatic transfer to the robotic work station for final assembly. With the elements of the production system known, it is possible to design building systems for automatic assembly. The analysis looks at typical housing construction exploring, masonry and wood framing building systems. Modification of existing construction processes and materials for automated assembly are accomplished through using the techniques of "design for automated assembly". Consideration is given to the difference between on-site and manufacturing plant application of these principles. This involves the relocatable nature of the work station (robot system) and the material flow to a movable work station, rather than a fixed one. The concept of work granularity and its effect on building system design for automated construction are introduced.

In order to demonstrate the system, a graphic simulation package is being implemented.

The simulator allows a model of the machines, materials,and processes to be built and graphically demonstrate the system operation. This model should allow analysis of automated construction systems without the expense of actual physical hardware and allow the feasibility of different building system models to be studied through graphic simulation. Thus, reducing the initial costs for research and development of automated systems for construction.

3. BACKGROUND

The use of automated equipment in on-site construction has been largely limited to the use of teleoperated devices such as cranes, earthmoving equipment, hand tools, and other types of material handling and processing devices. This is contrasted to the utilization of advanced machine and computer technologies in the manufacturing industries. New concepts in flexible manufacturing systems, group technology, robotics, artificial intelligence, computer-integrated- manufacturing, etc. have been primary factors in improved factory productivity. Only recently has there has been a substantial increase in the use of computer-aided-design systems in the construction industry. However, the development and integration of advanced machine technologies for construction has been limited primarily to the Japanese construction industry. Applications in both housing manufacturing and commercial building construction indicate the feasibility of advanced technologies in construction. Advanced technologies provide a means through which integration and automation can improve quality and reduce costs.

Since 1984, papers presented at the annual symposium on robotics in construction have indicated successful commercial applications as well as methodologies for research and development [RIC84, 85, 86, 87]. Automation in the Japanese housing industry has involved the operation of prefabrication plants where automotive manufacturing expertise has been implemented. These housing manufacturers have integrated computer-aided-design and computer-aided-manufacturing systems (CAD/CAM) that fabricate most of the building in the factory. [Carlson86]. However, research and development of advanced technologies for on-site housing construction has been practically non-existent and has been largely limited to on-site prefabrication of plumbing trees, ducts, and structural wood framing elements such as wall panels[Gatton84, 87]. On-site housing construction is typified by craft industries which use manual labor as the primary motive force. Due to the dexterity of craftsmen and the flexibility of design, an unlimited number of configurations can be produced. Most types of automation that are integrated into housing construction are performed off-site in prefabrication plants. Highly automated systems, such as those in Japan, require millions of dollars in capital equipment. This expenditure requires a market large enough to support such an investment. In Japan, where the markets are more concentrated, large capital investments are justifiable. However, in the United States, markets are more widely dispersed and would have more difficulty in supporting the investment [Guy84].

The utilization of robotics to perform on-site construction operations in commercial construction was initially limited to specific applications whose manipulative requirements were within the capabilities of robots. Although present applications have been hard pressed for economic justification, technical feasibility has been demonstrated. The use of a specialized robot to perform a specific commercial construction operation can be justified by the size, quantity, and repetition of that operation. As development costs are spread over the mass production of the system, and hardware costs are reduced, economic justification can be expected. Such an approach to housing construction, however, would lead to the same capital investment problems. The second generation of construction automation research and development in Japan has involved the modularization of robotic components and work elements [Hasegawa85]. This involves the separation of the individual robotic component's manipulative characteristics. The underlying concept is to allow a set of modules that have standardized interfaces to be configured into a whole system that has the manipulative capabilities necessary to perform a given task. This modular approach has expanded the capabilities and also revealed the fact that many operations, as they are presently being performed, are too complicated for automation. This problem has also been present in the manufacturing industry. The main issue has been discovered to be in the design of the product where consideration of the production process in design can have a major impact on the feasibility of automating the production process.

In construction operations, consideration of the principles of 'design for automatic assembly' [Boothroyd85] in the development of automated construction system has been identified as the third generation in Japanese research and development. The application of automation in construction must utilize the same automation technologies which are found in the manufacturing industry. These consists mainly of computer and robotics technology. Utilization of these technologies in the construction industry makes possible the integration of design, construction, operation, and maintenance of facilities to improve quality and reduce costs. The primary difference in applying automation technologies in the construction industry instead of the manufacturing industry is the scale of the product. This paper describes an approach for applying automated manufacturing technologies in the construction industry.

The most advanced systems utilized in the manufacturing industry are referred to as computer-aided-design/ computer-aided-manufaturing systems (CAD/CAM). These systems allow designers to design products on an interactive graphics terminal, often with the assistance of artificial intelligence. Once the product design is complete, the system generates all of the control commands necessary to manufacture the product. This is accomplished by the systems ability to develop a plan to utilize the available resources in the production process. When an existing product manufacturing process is automated, the largest savings are gained when consideration is given to modifying the design of the product and the components from which it is assembled.

Traditionally, the manufacture of the product's individual components and its final appearance were the main factors in design. The final assembly of the product relied on the dexterity of the human for accomplishment. In comparison to the most sophisticated machine, humans have sensing, manipulative, and decision making capabilities that are far superior. When efforts are made to automate a process that has been performed manually, an important factor is to determine if the assembly operations are within the capabilities of the machine. Often, though, the assembly of a product is too complicated for automation and a redesign of the product for simplification of the assembly process is necessary. The techniques involved in design for automatic assembly include: 1) minimizing the number of parts to be assembled, 2) use of self positioning devices such as guides and tapers, 3) designing components that are stable after positioning, or that can be built up in a layered fashion, 4) design of a work carrier that allows quick and accurate positioning, 5) designing parts to facilitate feeding and orienting, and 6) use of quick fastening operations [Boothroyd85]. The basic goal of these techniques is to simplify assembly so that the material feeding and manipulative requirements are within the capabilities of machines. Assembly can be defined as the joining of components into a finished product. The actual operations involved in assembly consists of 12 to 17 different types of motions, depending on which classification is used [CSAKVARY85]. Joining processes are accomplished by either 1) the shape of the components by interlocking, 2) gravitational, frictional or some other type of force, and 3) bonding of the materials. The assembly processes can be divided into three categories: 1) handling, 2) composing, and 3) checking. Handling involves the orientation of a component for the next step, composing, which involves the actual joining process. Finally, the assemblage is checked for conformance to the design. Similarly, in the construction industry, designs are translated into construct.on operations. These construction operations are also resources with certain capabilities and limitations. In order to develop automated construction operations, it is necessary to define an automated sytem with known capabilities.

4. AUTOMATION TECHNOLOGIES IN THE CONSTRUCTION INDUSTRY

The further introduction of automation into construction requires utilization of technologies that are presently applied in the manufacturing industry. These technologies include computers, robotics, group technology, flexible manufacturing systems (FMS), computer-aided-design (CAD), computer-aided-manufacturing (CAM), and computer-integrated-manufacturing (CIM). The primary difference between product manufacturing and construction lies in the scale of the product and the requirement to assemble the product on-site. The possible solutions to this problem involve large scale manipulators or moveable workstations to obtain the necessary work envelope. These solutions have been applied by the Japanese to high-rise construction. The application of manufacturing technology to housing construction has resulted in the development of highly automated prefabrication factories where most of the production is performed. These factories, however, require large amounts of capital investment and a correspondingly large market for support. These types of concentrated markets are not present in the United States. As a result, housing construction continues to be craft oriented and labor intensive.

5. AN INTEGRATED SYSTEM FOR AUTOMATED CONSTRUCTION

Building production is a complex assembly process that requires manipulative capabilities within a work envelope much larger than that found in the typical manufacturing plant. The ability to manipulate within this envelope can be accomplished in two ways: 1) Large scale manipulators, and 2) Mobile robots/ automated equipment. This research separates the mobility requirements from the process requirements. This allows the identification of a process definition module and a environmental mobility module as the basic elements of a system for automated construction.

The basic manipulative capabilities of the process definition module system consists of a robot with six degrees of freedom and continuous path motion capability. The ability of the robot to be reprogrammed allows it to perform many different operations. The characteristics of these abilities allow construction operations to be categorized, designed, and modified for automation. The environmental mobility module has a range of specifications. The mobility requirements may consists of manual, semi-autonomous, or autonomous capabilities. The various types of environmental factors affecting mobility lead to the identification of systems for smooth and rough terrain as well as the ability to position in the vertical dimension. Utilization of an on-site robotics system and the principles of designing for automated assembly in the development of integrated building systems requires one additional component. The building system that are developed must use available materials. However, these materials are not always in conformance with the requirements of the automated building systems. In order to process available materials, a flexible work cell is integrated with the robotics system to accomplish construction. The work cell is fed materials manually and, after any required processing, provide the materials for either manual or automatic transfer to the robotic work station for final assembly. The flexible work cell performs processes such as cutting, nailing, drilling, and assembling.

With the elements of the production system known, it is possible to design building systems for automatic assembly. The analysis looks at typical housing construction with the two main building systems of masonry and wood framing. Areas of potential modification of construction for automated assembly are identified through using the techniques of "design for automated assembly" [BOOTHROYD82]. This is accomplished through analysis of the work cell and work station activities with respect to the building system requirements. The building systems can be evaluated and ordered by their automated constructibility and by production analysis. The cost analysis involves both materials and machine expenses in terms of the relative productivity of different building systems. This allows identification of the attributes of the building system, the flexible work cell, and the work station that contribute to their feasibility and evaluation order. Additionally, the difference between on-site and manufacturing plant, which involves the relocatable nature of the work station (robot system) and the material flow to a movable work station, rather than a fixed one, introduces a new concept, called work granularity. This refers to the size of various work tasks and their distribution among the machines. A study of the effect of various combinations of work granules allows identification of patterns that correlate productivity of the building systems, work cell, and work station configurations.

The most highly automated construction processes have been developed by the Japanese construction contractors. Upon analysis of the applications of robotics to construction in Japan, it is evident that applications were based upon selection of operations which required manipulative capabilities within the limitations of available robotics. In the design of production systems in the manufacturing industry, the product is often modified from its original design so that the production process is simplified. This concept of "Design for Automation" is applicable in the development of automated construction systems. One problem arising in the design of new building systems is the availablility of components and materials for such a system. This issue is solved by a twofold approach: 1) The integration of a flexible work cell on-site, and 2) The limitation of utilizing standard components in the design of automated building systems. This flexible work cell would be capable of processing common construction components into specified components and locating these components for interface to an automated material handling system.

Given these conceptual machine capabilities and utilizing an integrated product development approach, building system utilizing available materials that can be processed, if necessary, by a flexible work cell can be designed. Different combinations of masonry and wood based structural systems may be studied along with other systems such as insulation, drywall, electrical, mechanical, and roofing, for a suitable building system whose requirements are within the production systems capabilities. Task that are beyond the system's capabilities and must be performed manually are also identified.

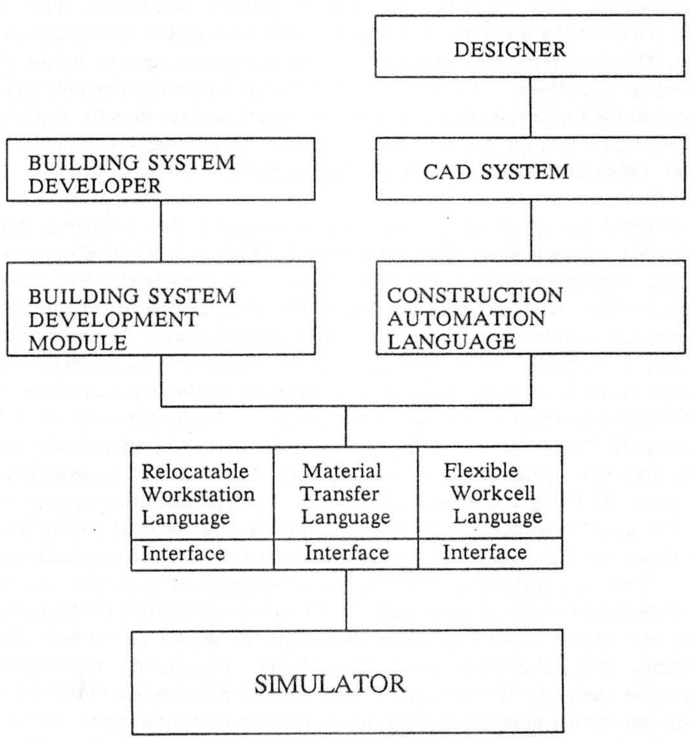
6. DESIGN FOR AUTOMATED CONSTRUCTION

According to Boothroyd, the technique for analyzing a design for automatic assembly involves three important steps: 1) an estimate of the cost of handling the part automatically in bulk and presenting it in the proper orientation for automated assembly, 2) an estimate of automatically assembling the part, to include any extra operations, 3) deciding whether or not each part must be separated from other parts in the assembly. The first factor to consider in rating a design for assembly is the actual parts that make up the design and the processes involved in assembly. The design can include variations resulting from different combinations of parts or it can be limited to the production of a single product. According to Boothroyd, the basic procedure in the analysis in analyzing a design for robotic assembly is to consider the costs of assembly utilizing a particular machine configuration. This requires that the production system components required to manufacture a design be known prior to any analysis. Classification charts are used to break down the assembly process into individual operations. These operations are structured to reflect the direction of assembly and the degree of difficulty. This data is compiled in an assembly time estimate. The costs associated with automatic handling and presentation are affected by the geometry of each part. Part geometry affects the ease with which a part can be fed and oriented. In construction operations, size will be a factor in process definitions. The analysis methodology breaks down the processes into charts, where each part is rated and feed rates are determined. The feed rates are compared to cycle assembly time to insure efficient utilization of feeding machinery. The costs incurred by the automatic assembly equipment is directly related to the workhead expenses. The workhead costs are directly related to the insertion process and are rated in a chart which considers factors such as the part stability, motion insertion requirements, and alignment characteristics.

The most powerful way of reducing assembly is to minimize the number of parts that compose the product. An estimation of the theoretical minimum number of parts indicates which parts of the assembly could possibly be combined into a single element. This is the primary method in which to reduce assembly costs. The criteria used to identify potential part combinations are: 1) relative motion of the parts during assembly, 2) necessity of using different materials in the parts, 3) affect of assembly or disassembly on the combination of parts into a single element. The identification of alternative methods for assembly through redesign is accomplished through an analysis of the product. This is done with the use of an "Automatic Assembly Worksheet" consisting of seven steps: 1) Get information about the design through drawings, prototypes, or existing versions, 2) Take the assembly apart, labelling each part, 3) Using a worksheet, break the required operations down into the requirements for each individual part 4) Re-assemble the product, completing the worksheet, 5) Complete the worksheet, 6) Calculate the total cost of automatic assembly and handling. From this worksheet, efforts to reduce assembly costs involve two factors: 1) Reduction of the total number of parts, and 2) Whenever the relative feeder costs or the workhead costs are shown to be high, then improvements should be studied. Also, low orienting efficiency indicate possible areas for redesign. Boothroyd recommends the following steps for re-design of the assembly: 1) When the theoretical minimum number of parts exceeds the actual number of parts, try to identify composite parts, and 2) If the maximum feed rate is less than the required feed rate, then check the feeding and orienting efficiency. Try to design parts which will reduce the complexity of feeding and orienting parts. If the relative feeder efficiency is low, identify beneficial changes. If the workhead cost is high possible improvements are in the insertion or fastening process. An additional factor in designing the distribution of work is the relative utilization of each part of the automated construction system. This includes the work cell, the material handling system, and the relocatable robotic work station. Indications that a particular component is under utilized during building system production show that by redefinition of the process, higher productivity is possible. Once these design changes have been made, re-evaluation can be done of the assembly cycle to compare the relative cost and identify any productivity improvement.

7. FUTURE WORK

In order to allow the system to build different configurations of walls, floors, and roof systems, a method to allow input of these specifications is necessary. A high level language interface for the fefinition of building systems and automated proecsses as well as a graphical interface for the designer will be developed. This will be a CAD interface which will allow designs that are within the systems construction capabilities. The system will allow quantification of the materials and work processes that are required to construct a particular design.



Existing CAD systems will be investigated for application to the system. The basic features of the system will allow the designer to configure basic wall, door, window, and roof elements for analysis and assembly. Work is being done on the Apollo network so that integration with the simulation package, which also runs on the Apollo network, will be simplified.

The use of artificial intelligence techniques in the system to optimize factors concerning design, planning, production, and maintenance of the constructed facility will be investigated. Currently, expert systems have found their way into the manufacturing industry with some success. These applications will be investigated to determine their potential usage in the automated design and construction system.

8. SUMMARY

The affect of design changes on the automated constructibility is evident at two levels. The first level is where design changes can be made in the building system itself and the associated automated construction processes that are necessary for production. The second level is at the conceptual design level where changes in configuration and specifications affect the final product design. The work presented here is concerned with the changes in building systems design and the associated automated construction processes. Initial analysis shows that by evaluation of process requirements for automated building system production, elements of the process can be identified that may improve productivity through process redesign. These changes take form in three ways. First, there is an actual redesign of the building system, second, a change may alter the production process at of a particular machine, and third, the distribution of processes over the different machines can be altered to make improvements.

These findings are similar to the approaches that have found success in the manufacturing industry. The primary difference is the handling of materials in respect to the requirement that the work stations are relocated at various points in time and the limitations in size that the automated construction system can handle.

9. PROJECT SUPPORT

This research project is one of many that comprise the program at the Advanced Construction Technology Research Center at the University of Illinois. The center is a unit of the University of Illinois College of Engineering and is administered through the Department of Civil Engineering. It is funded by the United States Army Research Office under the Department of Defense-University Research Initiative Program. The multidisciplinary research program is conducted by faculty and students of the university. The Director of the center is Professor Joseph P. Murtha. The center's research program is organized in the following five thrust areas: 1. Nondestructive Evaluation Technologies for Constructed Works 2. Construction Site Metrology 3. Computer-aided Construction 4. New Technologies and Materials for Building Construction 5. Special Technologies. The center's research goal is to advance the scientific and technological base necessary to support a major infusion of advanced technology into aspects of construction engineering to reduce significantly the life-cycle costs of facilities. We are grateful to participate in this conference and support the international cooperation in this great work of improving quality

and reducing the cost of construction through research and application of advanced technologies.

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