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AUTOMATION AND ROBOTICS IN CONSTRUCTION: A FEASIBILITY STUDY

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ABSTRACT

This paper examines issues which relate to the feasibility of using robotics in the construction industry. Major factors which will influence when and how robotic concepts and machines are implemented in support of the production process in construction are considered. The primary factors driving the adoption of robotics in construction are identified as need, technological feasibility, and the economics of implementation.

1. INTRODUCTION

The objective of this paper is to discuss the feasibility of applying robotics concepts to construction production processes. In order to concentrate on processes which have potential and exclude those processes which are not strong candidates for automation, brainstorming sessions were held with contractors in the Atlanta and Washington areas to select processes for further evaluation. The participants were asked to consider construction processes from the heavy and highway, building, and industrial construction areas.

One of the premises of the evaluation of each of the selected processes was that the driving force supporting robotization of a production process is the need and economic feasibility of the robotization. Counterbalancing this need, however, is the technological state of the art, which can either support or present formidable barriers to the automation.

The construction industry, in general, has been traditionally conservative in accepting new approaches. The industry traditionally has modified existing and proven practice to achieve improvement rather than trying altogether new methods. It appears that the rule of evolutionary, rather than revolutionary change will continue to hold, and that acceptance of robotization will necessarily be proceeded by an automation phase. That is, technology leading to a higher degree of machine and equipment automation will have to yield productivity improvement before full robotization will be accepted in practice.

Certain characteristics of construction processes are unique and complicate the implementation of robotization in construction in contrast to the utilization of robots in manufacturing or other industrial applications. The following sections discuss some of these characteristics of the construction environment which make the use of robotics a more challenging proposition.

1.1 Open Loop and Closed Loop Systems

In an article prepared for presentation at the "Symposium on Innovation in Computer Technology for the Building Industry" held in October of 1986, Kenneth Reinschmidt [2] of Stone and Webster Engineering Corporation in Boston discusses several aspects of the construction environment, which represent important constraints to the implementation of automation. The first of these characteristics addresses the open versus the closed loop nature of automation. In an open loop system, the loop is closed by the actions of a human controller, who intervenes to provide input and decision making. In a closed loop system, the machine is fully automated and no human intervention is required or expected. The level of sensing and artificial intelligence available to the machine is able to close the loop and the human operator becomes simply an observer. Reinschmidt notes that "... the major problem (in construction) is with the robots themselves. Virtually all the robots made today are open-loop devices. This means that the robot is pre-programmed to execute a given routine in space, with little or no sensory feedback... Consequently, many industrial robots are dependent upon human workers to close the loop and to make sure that the work piece is in the proper position for the robot to operate on it. In automated factories the loop is closed by the assembly line itself, which must bring the part to the robots in exactly the position and in exactly the orientation that the robots expect" [2].

Due to the dynamic and unstructured nature of the construction environment, it is improbable within the near term (the next 15 years) that true closed loop robots will be able to operate on the construction site. Open loop systems such as teleoperated machines, on the other hand, should appear much more quickly. Both the need for and the economics of such machines are compatible with the evolving picture of construction. The need, for instance, to develop machines to operate in toxic waste areas and handle toxic earth and fill materials should support development of remotely controlled heavy equipment. This type of teleoperated equipment can be viewed as a mobile open looped system.

1.2 The Problem of Shims

Actual locations of installed items in the field typically differ from the precise or "neat" locations given on the design drawings. For instance, openings for doors and windows typically vary in dimensionality from the exact dimensions given on the drawings. Prefabricated door frames and windows have to be modified or shimmed in the field to correct for these deviations or variations in the precise location of the openings.

Pipe spools typically have to be shimmed or fitted up in the field to maintain the line in conformation with the required alignment. If the pipes are prefabricated and then erected in the field without any fit-up correction, errors in the bends and angles accumulate along the line and ultimately lead to a failure to be able to hang the pipes properly. In other words, small errors in a single pipe spool tend to accumulate along the line.

Reinschmidt makes the following observation: "Of critical significance in the field is the stack-up of deviations, each of which is individually within construction tolerances. This build-up of tolerances may be enough to defeat automated equipment. The feedback of as-built dimensions can eliminate this problem... With feedback, succeeding elements can be adjusted to fit." [2]. This "problem of shimming" requires a high level of sensing sophistication. Although, the tolerances in construction are typically more generous than in manufacturing or the aerospace industry, the actual installation of items in construction will require very accurate metrology to establish the precise location of the interfacing elements.

This type of sensing is impacted by the dusty and unstructured nature of the construction site. Sensors on construction robots must be rugged and capable of resolving complex situations if they are to operate in an closed loop mode. Even teleoperated equipment using video cameras and similar vision equipment have encountered difficulties in the construction environment (e.g., Three Mile Island repair work).

The shimming question and the complexity of sensing requirements are also indicative of the qualitative aspects of construction, which are typically reconciled on the job site within the "skill" capability of the human worker. A good example of this qualitative skill aspect of construction work is the shotcreting of underground tunnels. The construction of tunnel liners in fragmented rock to stabilize the fracture zone is accomplished using shotcrete. The material is sprayed onto the tunnel wall in order to achieve a layered build-up until the required thickness is reached. A number of qualitative (artificial intelligence related) aspects to this operation require very sophisticated sensing. Among the qualitative considerations are:

a) The "reading" of the application surface to insure proper bonding of the shotcrete to the base material (i.e., the rock wall) is occurring.

b) Evaluation of the layering and "set up" of the shotcrete to insure that the inter-layer bonding provides sufficient support so that the applied material will not fail and fall due to an exceeding of the bond strength of previous layers.

c) Determination of the liner thickness, which is required to control the fracture zone (Note: This is normally done intuitively by the equipment operator).

These are just a few of the qualitative considerations, which the human operator is continuously sensing and integrating into his decision pattern regarding the application of the shotcrete.

Although a shotcreting "robot" has been developed, it is not clear how successful this machine has been at overcoming the types of "skill" related actions referred to above. The robot does require the intervention of an operator and functions as an open rather than a closed loop system.

1.3 Material Flow Considerations

Unless material can be fed to the robotic device with sufficient speed, the economics of automation will be undermined. Unless off-setting considerations, such as worker safety and health justify a high level of machine idle time, the capital cost of an automated machine will not be justified.

Certain types of construction operations, on the other hand, are not constrained by material flow considerations. Operations which involve surface treatment (e.g., painting, bush-hammering, etc.) are not material feed constrained since the robotic device passes across the "material" to be processed. This would indicate that surface processing operations in construction would be good candidates for the application of automation and robotics.

The application of robots to earthwork operations recognizes that the "material" to be processed normally is available in large quantities. This means that the "feed" problem is normally not a major constraint. Automation of such operations as grading and entrenching have been reported [1]. Protypical excavation robots designed to seek subsurface pipeline leaks and repair them are under development at Carnegie-Mellon's Robotics Institute [4].

The material feed problem may also be tractable if the applied material is fluid or semi-fluid and sufficient area or work space is available.

1.4 Metrology Considerations in Construction

As noted above in discussing the "problem of shims," metrology or the science of measurement will be critical to the implementation of robots in the construction environment. Since the assembly process in construction takes place in the unique and unstructured arena of the project site, navigation of mobile machines and precise definition of location both in the macro (machine) sense and in the micro (e.g., effector arm, work position) sense present formidable problems to the use of automation and robotics. Human intervention within the context of open loop systems is presently required to reconcile many of the positional and locational problems.

The equipment to establish precise metrology on the construction site exists although field testing of such equipment to evaluate performance on actual projects has been non-existent.

The problem of the data transmission and data base support required to make site metrology available for navigational purposes and work face definition is formidable. This appears to be the major area in which research is required. Although acquisition of meterological data is presently feasible, the organization of the required data structure needed to support robotics devices and the routing or transmission of the data to the machines will require development of compatible data protocols. In the manufacturing area, General Motors has begun to address this problem within the context of the system called Manufacturing Automation Protocol (MAP).

In addition, a great deal of research into the construction processes themselves is required in order to establish what kinds of data must be acquired, structured, and transmitted in order to establish machine control.

In this study, an attempt has been made to diagram, the selected processes in order to identify elements for analysis and establish data parameters which limit or support robotization.

2. FEASIBILITY ANALYSIS

Robotization and Automation of construction industry is an important step forward in the industry. For each construction process to be automated, it is necessary, on the basis of a detailed analysis, to determine the more important basic problems of automation and commence the solution of these problems by a systematic approach. This analysis is based on an evaluation of need, technological feasibility, and economic feasibility.

2.1 Need Based Feasibility

Need is a motivating factor in robotization of construction operations. Closely related to need is the concept of the economic viability of robotization. That is, if the need is sufficiently great, the economic payoff will offset the development expense required to overcome technological barriers. Tucker [3], for instance, has noted that the major cost center in industrial construction is piping. If the fabrication and erection of piping can be improved by automation, the economic benefits can be calculated in terms of billions of dollars.

The assumption here is that certain characteristics of construction production processes make them well adapted to the use of automation and ultimately robotization. Further, need will justify the expenditure of development dollars to perfect and market the robotic device. Ten characteristics supporting the need for robotization have been identified as follows:

1) Labor intensiveness
2) Vanishing skill area
3) High skill requirement
4) Precision and dexterity requirement
5) Repetitive in nature
6) Tedious and boring
7) Critical production activity
8) Unpleasant and dirty
9) Hazardous to Health
10) Physically Dangerous

The first step in the overall effort of evaluating feasibility of automation and robotization in construction is to determine the principal driving force motivating an interest in robotization. Essentially, this reduces to the question as to what aspects of the construction industry should become more automated. More specifically, what are the needs or demands which fuel the effort to attain higher levels of automation? In order to focus on these needs, a panel was formed. Members of this panel included experienced practitioners in design, construction management, construction operations, and construction research. Brainstorming sessions were held, the goal being to identify the specific characteristics of a construction process which would make that process a strong candidate for automation or robotization. Obvious selections were processes which are dangerous, highly labor intensive, and repetitive in nature. The final result of this brainstorming effort was the definition of the ten needs listed above.

2.2 Technological Feasibility

Another basic tenet of this study is that the automation of robotization of a selected process must be technologically feasible within the context of the existing or projected state of the art in robotics. The technological evaluation for a construction process must consider both present technology and developmental trends in robotics research. The greater the near term availability of a particular support technology, the higher the numerical rating given for the feasibility of robotization.

The technological areas against which each construction process was evaluated included:

1) Material handing requirements
2) Required sensor technology
3) Complexity of required control software

4) Control Hardware
5) End effector requirements

Material handling, per se, is technically not an intrinsic or connected part of the essential automation system, as are the other four. However, unless some automated form of material delivery can provide a steady stream of material to be processed, the benefit of a highly automated production process will be negated. The relationship between the speed of processing and the speed of delivery of material is critical to the concept of automation of construction processes. Automation of manual processes would presumably lead to even greater machine idleness unless material flow rates compatible with the speed of the processor can be developed. Processes involving no material supply constraints are the strongest candidates for robotization from a material handling point of view. A good deal of progress in material handling has been achieved in the industrial sector. Some of the concepts used in manufacturing may be transferable to construction processes.

The second major technological area considered is that of sensors. Sensors are used essentially for performing the measurement tasks required for an automated machine to perceive and define its environment. These sensors are generally of the "tactile" or "vision" type and enable the automated equipment to locate itself, its surroundings, and construction materials and equipment. In addition, sensors allow machines to identify or verify particular objects, complete inspection processes, and provide guidance data to the functional mechanisms which will actually perform the work.

The third technological area considered is that of control software. This is the "brain", which accepts data and directs decision making. The automated systems developed to carry out this function rely heavily on the concepts of artificial intelligence. The control software includes data bases which supply the enormous amount of information required to automate most construction processes. Present thinking in the industrial sector envisions transfer of design information from CAD systems to those data bases supporting the robot. This will require improvements in the areas of data compatibility and integration. The control software must also be capable of processing sensor data and the control signals used to actuate the robotic hardware. Interfaces are required to allow access to a variety of databases and hardware control systems. Knowledge engineering will be required to allow the automated machine to make decisions based on heuristic search methods.

The fourth of the technological areas included for evaluation is control hardware. This addresses the actual hardware, which processes the construction material or performs the required function (e.g., inspection of tiles, etc.). Control hardware includes the energy and mobility systems required as well as the processing hardware itself. Presently, a wide variety of actuators and manipulators to execute construction functions exists. These devices, however, concentrate on the use of mobile end effectors, which process the material or apply a fluid material to accomplish the required work. Most of the existing systems have been developed for industrial fabrication and require modification for use in the construction industry. Construction poses special problems in terms of heavier loads, longer reaches, and unstructured and dynamic physical environment.

The fifth and last technological area considered is that of end effectors. End effectors are the functional devices attached to the end or wrist of a robot arm, which perform the final task of processing the construction material. End effectors are often called end-of-arm-tooling, and can be classified as hand tools, hand/tool holders, or micromanipulators. Their functions include grasping, installation, placing, or removal. They can be thought of as the equivalent of the human hand, and in many instances these devices are designed to closely resemble a hand, with a palm, fingers and joints. In other cases, there is no resemblance at all to a hand, as in the case of specific function devices, such as a nailer. Although considerable progress has been made in this area, more is needed for adaptation to the construction environment. Fortunately, a significant amount of research relating to this topic is currently underway.

2.3 Economic Feasibility

Economic benefits of automation and robotization in construction are basically due to: a) productivity improvement; b) quality improvement; and c) saving in skilled labor.

The first main factor in economic analysis is productivity improvement. Productivity can simply be defined as the ratio of output to input, typically given as units produced per man-hours required. A comparison between productivity of the current system and the proposed robotic system should be made. If historical data on productivity is not available then a study to determine these values must be made. If a construction operation is automated or robotized, it is expected to have an increase in productivity to absorb the cost incurred in robot implementation. Obviously, productivity improvement is not the only factor that pays for the robot.

The second factor that must be considered in economic analysis is quality improvement. Quality improvement based on the use of robotics is founded on the idea that machines will produce a better quality compared to that of traditional systems. Quality of a construction product can be measured by a numerical model, which considers such characteristics as strength, dimension, color, etc. Only the relevant characteristics of an operation product should be considered. There is a direct correlation between cost and level of quality improvement.

The third factor is savings in labor cost. Savings in skilled labor is a prime issue in justifying a robot in the long term. It is anticipated that the key motivator for construction robotization will be the saving of labor cost by supplanting a human worker at least in part with a robotic device. High and rising labor costs can be expected to accelerate the utilization of labor saving technology in general, and automation in particular. However, many of the intangible indirect costs associated with bringing a robot onto the construction site and maintaining it are often overlooked.

3. SUMMARY AND CONCLUSIONS

Certain characteristics of the processes which rank as highly feasible from a technological point of view can be identified. Processes which are related to processing of surface areas (e.g., sandblasting, bushhammering, concrete finishing) and either require no material application (e.g., concrete finishing, bushhammering) or have to do with the application of a fluid or semi-fluid material (e.g., sandblasting, shotcreting) have high rankings. On the other hand, those processes which rank low in technological feasibility require complex operations involving the movement, attachment, etc. of solid components or objects to a fairly high level of precision (e.g., plumbing, structural precast).

Although automation to increase worker productivity is possible in such processes as forming or plumbing, the level of technology in sensors, artificial intelligence, and allied areas is not presently available to support closed loop automation of such activities. The problems of "shimming" and feed of applied or processed material, still present formidable problems to true robotization of processes involving the manipulation and installation of solid components in the dynamic environment of the job site.

The mobility requirement can only be accommodated with a new level of technology, which allows the mobile robot to sense its position in real time (as a human does). Efforts are underway presently to aid mobile equipment in establishing position within the unstructured environment of the job site. In discussing the robotization of earthmoving and hauling equipment in relatively well-defined situations, such as fixed route hauling between borrow pit and fill location, the parallel between this situation and the control of aircraft moving between airports is often cited. Technology is available to automatically take-off, fly and land aircraft without human intervention. If this is the case, why can't this be applied to operation of trucks on the haul? The answer is, of course, that a multitude of electronic reference points are available to aircraft moving from airport to airport. This electronic network of reference provides metrology for the aircraft to use in determining position. Obviously, a similar network of reference metrology would be needed to allow haul units to determine position and trigger actions to load, accelerate, decelerate, etc.

Economic benefits associated with improved production and quality on large industrial plants may support robotization for processes which are weak candidates based purely on the hazardous environment criterion. The best example of this economic benefit driving automation developments is the induction bending of industrial piping to reduce welds and increase productivity and quality. For processes which contribute significantly to the overall costs of a construction project, automation to reduce skilled labor requirements and increase productivity and quality will often support developmental costs.

Several points appear to be central to the development of robots for the construction industry based on the research to date: 1) Inspection tasks appear to be well adapted to automation and robotization; 2) Operations in unsafe environments offer excellent opportunities to apply robotics or teleoperation, and economics and worker safety considerations support significant developmental investment to robotize unsafe and dangerous work processes; and 3) The application of robotics to processes with significant economic potential (e.g., piping in industrial construction) may be justified if the synthesis of existing technologies support a high probability of successful development.

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