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Development of the integrated Construction Automation Methodology

Abstract

Current research in construction automation is focusing on automating individual processes instead of approaching the problem from a hierarchical systems viewpoint; thus many systems being studied treat the construction site as a "hostile" environment and incorporate many sensors to extract information from the building. As a result, sensor and signal processing technology can be a limiting factor in the design of machines to automate building processes. However, if integration and automation of the construction process are approached from a systems view, then existing technology can be used to design economical machines to automate many construction processes, and to coordinate and integrate their use within the construction environment. A new design methodology, the Integrated Construction Automation Methodology (ICAM), is presented here to assist in achieving high levels of integration and automation using existing technology.

1. Introduction

The U.S. construction industry has had a net loss of productivity of almost 3% a year since 1972 [1]. To reverse this trend, the industry must automate. Automation is no longer an issue of labor/management acceptance, it is required for survival. As the manufacturing industry has learned, "Computers or programmable devices in the hands of a highly motivated workforce appear to be the solution to many of our manufacturing challenges"[1].

A construction site is a complex system involving many disciplines operating simultaneously; thus automating construction processes and integrating them into the overall process will require identification and decomposition of system and subsystem tasks using a hierarchical control strategy implemented through a local area network at the site. This type of control strategy will allow real time modification of processes and their completion sequence; thus making the system adaptive to the often varying construction environment.

Although strategies for integrating and automating the manufacturing process and the construction process are similar (e.g. hierarchical control of computer controlled machines), the construction

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1 R.J. Eaton, General Motors Vice President, Advanced Product & Manufacturing Engineering at the first Manufacturing Automation Protocol (MAP) demonstration, National Computer Conference, July 1984.

process takes place where workers and machines must function in often poorly defined, harsh operational environments. Thus to increase the chances of success, teamwork and cooperation among machines and processes must be designed in and integrated at the systems level.

To help coalesce the fragmented construction industry, a method of attaining these goals is being developed by the author. The Integrated Construction Automation Methodology (ICAM) will help automate the construction process by integrating building, machine (robot), and process design on a systems level. Initially it will be developed and demonstrated for application to automation of large building construction.

This approach is currently being studied by the author at MIT. The following describe in greater detail the problem definition and the methods being developed to address the issues involved in integrating and automating construction processes.

2. Problem Definition

Although sophisticated software tools are available for managing construction projects, success of the project still relies on sub-contractors and workers to carry out tasks and report the results. This results in islands of modernization that lack compatibility at the management (computer software/hardware) level and the implementation (machine and process automation) level.

Currently there does not seem to be a coordinated effort between building designers, contractors and machine designers to automate the construction process on a systems level. As a result, a trend is forming towards development of independent automated machines which require sophisticated sensor and information processing technology. Hence these machines will be costly and difficult to implement in practice because of current technological limitations.

In order to overcome this problem of fragmentation and expensive automation, standard interfaces for construction integration between computer software and hardware tools currently are being identified, developed, and synthesized. This will allow computers to schedule, coordinate, and control project tasks. Under computer control, statistical quality control data can be obtained, thereby allowing for optimization of construction processes. In addition to computer scheduling of project tasks, computer controlled machinery for automating construction processes is also being developed by the author.

The construction industry has considered its working environment too hostile to be economically automated (e.g. dirt and temperature extremes as well as ill-defined processes). Indeed ad-hoc automation will be expensive and will thus have limited use. This paper will show that it is possible to bring the construction process under control if integration and automation are approached from a systems design level.

2.1 Objectives of ICAM

In manufacturing, the size of the machine dominates the process; building construction processes, on the other hand, are usually much larger than the machines. The key to construction automation, therefore, is to use the building system itself as a "machine conglomerate" with machine elements as distinct degrees of freedom within the "machine conglomerate" (building). Thus the objectives of ICAM are:

1) Develop a design methodology to integrate building design with machine design for automation. Application of the methodology should yield a matrix of functional specifications for machinery and processes needed to automate a particular construction project.
2) Develop basis for a hierarchical control system for controlling an automated construction site. Specifically, a generic sensory interactive control system and data base for use with families of computer controlled machines.

2.2 Research Trends In Construction Automation

The term "construction automation" conjures up images of androids running around with hammers and shovels. Similarly, with the advent of computer controlled machinery, people envisioned multipurpose android type robots producing all our goods and services. However, early forecasts of widespread use of autonomous robots by the mid 1980's were too optimistic [2]. A human's sensory system and intelligence are not easily duplicated by machines. This experience led to modeling and design of well defined processes which could be executed by simple computer controlled machines [3,4].

In a laboratory environment, mechanical designs of robots are capable of performing most manipulating operations that would be required for automating many construction processes. However, current designs are too complex for application in a hostile construction environment. Furthermore, current sensor and information processing technology is very limited in its ability to adapt to varying environments and locations. Thus it is not recommended that an attempt be made to adapt general purpose robots for use in a construction environment. Two papers [5,6] provide an excellent overview of research in construction automation, and they affirm that the Japanese are presently leaders in this field.

The Japanese are leaders in construction robotics because they have an aggressive research, development, and implementation program. They realize the power of combining electronic and mechanical systems to create "smart" special purpose machines (i.e. mechatronics). For example, they have used their "balanced earth tunneling method" to build a tunnel in San Francisco using remote controlled machines. Schimizu Construction and Kobe Steel have developed a robot for applying rock wool fireproofing insulation to steel structures. The Japanese are also good at developing large systems, such as entire factories on a barge which they can ship to location (e.g. a pulp mill for use in the Amazon).

The Japanese, however, do not seem to be focussing attention on a long term goal of a coordinated systems approach to construction integration and automation, based on hierarchical computer control of the entire construction process. They are in the process of developing a number of construction robots for varied applications (non-integrated) including [7]:

1) Robots for erecting steel structures,

2) Robots for welding at site,

3) Robots for finishing concrete floors,

4) Robots for erecting and dismantling scaffolding,

5) Robots for cleaning onsite,

6) Robots for applying sealant to exterior walls,

7) Robots for painting,

8) Robots for decommissioning,

9) Robots for applying insulation,

10) Robots for tunneling.

Reference has not been found with regard to application of a computer controlled machine to help construct (assemble) a building in the U.S.. The trend seems to be towards increased use of prefabricated sections, many still made by hand offsite, that are assembled by hand onsite. However, U.S. researchers lead in advanced robot design and artificial intelligence technologies and are applying them, for example, to mobile robots for operation in nuclear and undersea environments [8,9]. Researchers at Carnegie Mellon University are working on robots for cleaning up Three Mile Island. Also researchers at Stanford University in cooperation with Unimation have added wheels to a six axis robot to enable it to travel 40 ft. and stop within inches of its target, but accuracies on the order of 0.050" are needed for most building construction processes.

2.3 Conclusions on Applications of State-of-the-Art Robotics Technology to Construction Automation

The absence of technology required to fully emulate human construction workers will preclude full scale automation of existing construction processes on an individual basis. However, if machines for automating construction processes are designed in conjunction with the building, then existing technology can be applied to provide a far greater degree of automation than is currently believed to be possible. This conclusion is based on the following observations:

1) Global position of a robot within a building is not easily achieved using onboard sensors; however, position can be determined with respect to structural members or radio frequency emitting wires in a concrete floor.
2) The lack of available vision and tactile information processing technology can be compensated for by keeping the building site clean and well ordered. Also, by design for robotic assembly, many processes can be automated without the need for elaborate vision systems.
3) The dexterity of a human construction worker cannot be duplicated by any machine, nor are designs likely to be developed in the near future.

Mechanical and electro-mechanical systems are principal limiting factors in integrating and automating construction processes. Another limiting factor is the methods by which the mechanical systems are to be controlled.

3. Artificial Intelligence and Expert Systems for Controlling Automated Machinery

In the early 1960's, some researchers envisioned computers as soon being able to act as universal language translators. This goal was never met because the rules of translation are not straightforward, they often require creative thought. Similarly, Artificial Intelligence researchers envisioned thinking computers which could be used to control disordered processes. This goal has not been met, because intelligence is being able to come up with new conclusions from old facts, where these conclusions are not based on IF THEN conditions. It would seem that the basic physics of computers and computer languages (they are binary yes/no systems) will seem to limit them to applications of problem solving paradigms (Expert Systems) [10].

It is true that expert systems will be a key to loosening required restraints on a process and giving machines more freedom to operate in less defined environments, but artificial intelligence to decide what to do in a new type of situation will not be available for many years [11]. Once expert systems are developed, if the machine encounters unfamiliar difficulties, the machine can supply data to a remote operator who can assess and correct the situation.

3.1 Hierarchical Control Strategies for Controlling an Automated Construction Site

The principle of hierarchical control is based on a tree structure wherein each computational module has a single superior and one or more subordinate modules (or interfaces to mechanical systems). Goals and plans are generated at the highest level which are decomposed at each lower level into subgoals. This continues until work required to complete the overall goal is distributed to simple machines in the form of simple tasks [12]. Information gathered during execution of the task is reported to the control system for statistical quality control analysis. This type of control strategy is needed to allow the system to adapt to the often varying construction environment.

On a large research scale, a hierarchical control strategy has been implemented in the Automated Manufacturing Research Facility at the National Bureau of Standards [13]. In order to apply hierarchical control strategies to control an automated construction site, many developments are needed such as: a central database, an understanding of the processes (to the point where the processes can be automated), a rugged Local Area Network (LAN), and computer controlled (or human assisted) machines.

For a family of machines to complete a group of tasks, they will have to share information. This implies the development of a generic sensory interactive control system for use with families of computer controlled machines. The structure of the controller would be hierarchical and modular. For the machine to be able to react to changes in its environment in a reasonable amount of time the controller would operate in real-time. Note that only the lowest level of the controller, which interfaces directly to each machine, would be machine specific.

The machine control systems would have the capability of interfacing with a central controller. The central controller would be a more elaborate structure of the basic generic controller. The machine controllers would have the capability of accepting data from a data base within the central controller. The data would be high level command instructions which the controllers would decompose into subtasks to be performed by the various elements of the machines such as sensors and actuators.

A hierarchical structure for the use of task decomposition is helpful in modularizing the complicated systems, in particular the central controller. By making the system modular, one can add or make changes to the levels of the system easily. Different machines will be performing jobs which require different sensory and actuator systems to interface to the machine's control system. Each sensory and actuator system will require a separate module within the control level with which it interfaces.

Development of this type of control system is needed for the control of a family of sequentially operating construction robots (or any other machine family). In addition to receiving instructions from the central controller, each member of the machine family would need to be capable of feeding back information about its completed process to the data base. The information would then be used by a following machine to compensate for errors in a previous machine's process. Thus, the feedback information would be used to facilitate machine learning to enhance online quality control.

4. Development of the Integrated Construction Automation Methodology (ICAM)

The Integrated Construction Automation Methodology (ICAM) is a systems design concept that integrates design, functionality, and constructability using the principle of harmony to avoid adversity between automated machines and the building, thus allowing integration of building design with machine design to automate construction.

"Harmony" between a machine and a process requires the machine to execute the process in as simple a manner as possible, and without having the results generate conditions adverse to other machines whose processes may build upon the first. In fact, sequential processes must be able to rely on the quality of the first process so the next machine and process can be simplified. "Adversity" between a machine and a process is requiring the machine to be able to process extra information in order to accomplish the job. An example is to require robots to have vision to pick parts from a bin. It is much simpler and more economical to present the parts to the robot in an ordered manner.

An example of "Harmony" in construction automation is to use the building system itself as a "machine conglomerate" with machine elements as distinct degrees of freedom within the "machine conglomerate" (building). Since buildings are cartesian systems, instead of trying to build a machine and guidance system to move in three dimensions, one can build the steel framework as a giant series of machine axes with integral bar codes describing location, function, etc. As a machine completes a task, it may leave a coded message that is used to guide following machines, with all information stored (and continually updated) in a central database. This requires the building and integration/automation plan to be designed together as a system.

In order to develop this type of systems approach, the problem must be defined with respect to goals and technology. Thus the first step towards integration and automation of building construction is to identify and classify types of designs, processes, and tools currently used with respect to how they can be automated and integrated into the global process, namely:

1) What are the short and long term benefits that will result from various levels of automation of a process (machine design and possible modification of the process) using existing technology.
2) What are the long term benefits of developing new technologies to automate a process, or develop an entirely new process that can be automated, while meeting functional performance specifications.

3) Will the system lend itself to partial or total integration with the global construction process.

Also related is the type of research (short, medium, and long term) required to automate and integrate an individual process, which can be assessed based on the following:

A) Can the process be automated and integrated in its present state using applications of existing technology? (short term, 1-5 years). In the short term, automation of specific processes will be limited by present technology to those that require a great deal of relative accuracy and take place along well defined continuous paths (no corners). Processes which do not require accuracy but have discontinuous paths can also be automated.

B) Is the process fundamentally simple and efficient, requiring only skilled labor (and undeveloped technology to emulate the skilled labor) to execute it? (medium term, 5-10 years).

C) Is the process too complex to be automated and integrated using current technology or technology that is likely to become available in the near future? (long term, 10 + years).

Among the processes involved in design and construction of large buildings, the following are rated as to the time frame required to automate and integrate the process (s-short term, m-medium term, l-long term):

1) Functional specifications of building defined (s-l).
2) Building form and detailed plans defined by architectural/engineering firm:
   a) building's site (s-l)

b) building's structural design (s-l)

c) building's exterior (s-l)

d) building's interior (s-l)

3) Prepare site:

a) excavation and grading (l)

b) utility connections (water, sewer, electrical) (l)

c) road building (l)

4) Construction of the building:

a) foundation (l)

b) structural skeleton (m)

c) construction of the interior:

1) interior wall framing (s)

2) ductwork (m)

3) plumbing and electrical (l)

4) drywall (s)

5) tape drywall (m)

5) paint interior (s-m)

6) flooring (s-m)

6) elevators (l)

d) construction of the exterior:

1) facade (m-l)

2) windows (m)

3) painting/weatherproofing (m)

4) roofing (m)

If executed individually, automating most of the above processes will require accurate positioning capabilities, assessment of the environment, and emulation of skilled manual labor. Thus it would be very difficult to automate many of these steps on an individual basis. If designed and executed as a building system, however, the task of automation becomes more tractable.

From this point, ICAM will assist in the systems and machine design phase. Specifically, ICAM will help evaluate elements of a design matrix of requirements (functional specifications) to automate and integrate construction processes by executing the following functions:

1) Specify functional requirements for the building, and develop conceptual designs of the building.
2) Identify building construction processes.
3) Formulate machine and process design matrix of functional specifications for automating and integrating processes (wish list).
4) Formulate a list of technologies (existing and/or future) required to automate existing processes. Evaluate the degree of integration (total or partial) that can be attained.
5) Assess available technology (and economics of implementation with respect to 4).
6) Evaluate physical information available from processes that may also be used to guide other processes (e.g. the position of a structural beam).
7) Optimize machine and process design design matrix by matching sources of information and processes which need similar information in order to be executed. (i.e. match information that is available or lacking).
8) Design, build and integrate test systems.

Steps 6 and 7 are critical to adapting existing technology to the problem of integrating and automating construction processes. Once the design matrix is optimized, a detailed execution plan can be formulated for the entire system because the matrix identifies inputs, outputs and technology required for machines to automate specific processes within the system.

5. Conclusions

ICAM will be a first step in developing an organized systems approach towards automating the often fragmented construction process. Completion of this research can have the following impact in the construction industry:

1) It will help to organize and integrate the building, process, and machine design processes; thus helping to eliminate the fragmentation that currently exists.
2) In the short term, large increases in productivity in some processes will be realized.
3) In the long term, ICAM will lead to development of an expert system and machinery - as appropriate technology matures - that will optimize design and construction of entire building systems, with resultant dramatic increases in productivity. The methods developed will also be adopted for use in automating other large scale operations.

Ultimately, adoption of ICAM will lead to an integrated construction site that will consist of workers, and computer controlled machines all coordinated by a central operations computer. Using a hierarchical control strategy, the computer will instruct men and machines to perform tasks which may be decomposed into sub-tasks until they are physically completed. Progress will be continually reported back to the central computer which will use this information to update scheduling of tasks. In addition, it will allow the entire building process to be statistically analyzed and optimized [14].

Furthermore, ICAM will provide a new systems engineering tool for developing automated and integrated construction processes. Examples of additional work needed are: Artificial Intelligence researchers to develop expert systems to apply ICAM for use by the designers of buildings and machines. As a result, sensors and information processing researchers will have areas of critical research identified (singularities in the design matrix which will require a human to correct). Also, mechanical design researchers will have functional specifications defined so they can concentrate on machine design and not have to try and figure out a process that is foreign to them.

ICAM can enable the construction industry to achieve gains in productivity, quality and safety. It will do this by laying the foundation for Computer Integrated Construction (CIC) systems that will control and automate the building and design process from conception thru construction. Ultimately it will also help tie together all the professions involved in the complex building process.

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