CURRENT STATUS OF CONSTRUCTION AUTOMATION AND ROBOTICS IN THE UNITED STATES OF AMERICA

Panel Discussion Paper
by

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ABSTRACT

Construction automation and robotics research and development in the United States is more than a decade old. A number of research institutions, universities, construction equipment manufacturers and construction engineering firms have been involved in these efforts. This paper summarizes the recent American accomplishments and current efforts in several representative areas. It is concluded that the United States research and development community seems to maintain its leadership primarily in construction automation software design and software engineering. However, a more intensive effort and dedication to automation concepts is needed to capitalize on the potential benefits of automation, particularly in the practicing engineering community and among the industry practitioners.

Introduction

Automation and robotics has been in all likelihood the most challenging endeavor in the American construction engineering academic community over the past decade. Similar enthusiasm for this field has been shared by several government and private research institutions and laboratories. The industry, including design and construction firms, material suppliers, equipment manufacturers and owners, with a few notable exceptions, was somewhat slower in relating itself to this new field of research and development activity. However, the process of disseminating the early results from the research and development community to industry practice is now slowly beginning to take place.

There are no universally adopted definitions for the terms 'construction automation' and 'construction robotics.' For the sake of our discussion, we will assume that 'construction automation' refers to the engineering or performance of any construction process, on-site or off-site, by means of teleoperated, numerically controlled, semiautonomous, or autonomous equipment. 'Construction robotics,' as discussed here, refers to advanced construction equipment exhibiting any level of capability related to teleoperation, sensory data collection and processing, numerically controlled, or autonomous task performance.

The primary "technology drivers" for introducing robotics to construction sites in the U.S. were health and safety hazards to workers from chemical or radioactive contamination. In extreme cases, where human access to the jobsite is impossible due to excessive levels of contamination, performance of the required work tasks can only be accomplished through the use of robots regardless of the associated cost. On-site experience with robotics in these environments, as well as in underwater and outer space tasks, has provided the developers of robotic systems with valuable lessons with respect to the practicality of certain robot design and task implementation solutions.

The underlying incentive for automating construction tasks is potential labor savings once the new technology proves successful. Although the U.S. has not experienced acute labor shortages in the construction industry similar to those in a few other developed nations, there appears to be a significantly diminishing number of skilled construction workers at this time. There is also a potential for a shortage of labor in the future due to demographic reasons. Hopes for expanding the construction activity into difficult work environments, improving construction productivity and quality through the use of automation on jobsites are also frequently mentioned.

Relevant Systems Developed to Date

A number of relevant robotic prototypes have been designed and built in the United States. Table 1 includes a partial listing of some of the robots developed to date. Some of these robots have already found commercial application and some only await commercialization by interested parties. Most of the developed systems have been inspired by either a compelling need to robotize a given task due to inherent hazard to humans associated with its performance, or by potential labor savings due to task simplicity, high volume and repetitiveness.

A number of other robotic prototypes and working systems have been developed for applications which are potentially transferable to the construction industry. These include areas of underground mining, underwater inspection and search, nuclear power plant decomissioning, structural assembly in outer space, military applications, and others. Even a summary description of those systems is outside the scope of this paper. Specific information on their details is available from publications by the Robotics Institute of America, commercial vendors, and professional associations such as American Nuclear Society, Institute of Electrical and Electronic Engineers, American Society of Mechanical Engineers, and American Society of Civil Engineers.

When analyzing the initial American approach to construction applications of robotics, it is apparent that a significant number of prototypes designed to date have been developed to mimic to a considerable extent the work of humans in unstructured jobsite environments. This approach neglected the need to restructure the jobsite environment to meet the capabilities of relatively unsophisticated, and thus frequently easier to build and more cost effective, construction robotics. As a result, the practical application of the early prototypical systems frequently proved very difficult or prohibitive due to a high cost. On the other hand, the positive side of that approach was valuable experience gained in such areas as sophisticated robot control systems, sensory data processing, artificial intelligence concepts, and machine learning. Significant advances have been made in autonomous navigation, intelligent real-time sensing (particularly in robotic vision), 'virtual reality' modeling, and data integration techniques. Future construction robotics have indirectly benefitted from a few one-of-a-kind robot prototypes developed on special orders from government agencies such as the U.S. Department of Energy, pushing robotics technology development to its new heights. This progress in technology has also been helped by the fact that for robot designs intended for disaster handling operations such as a nuclear accident at the Three Mile Island in Pennsylvania financial and economic constraints were not viewed as important.

Robot Type	Application	Developer
John Deere Excavator, Model 690C	teleoperated excavation for rapid airport runway repair	John Deere, Inc., Moline, Illinois
Laser-Aided Grading System	automatic grading control for high-volume earthwork	Gradeway Construction Co. & Agtec Development Co., San Francisco, California; Spectra-Physics Co., Dayton, Ohio
Automatic Slipform Machines	placement of concrete sidewalks, curbs and gutters	Miller Formless Systems Co., McHenry, Illinois; Gomaco, Ida Grove, Iowa
Micro-Tunneling Machine	teleoperated micro-tunneling	American Augers, Wooster, Ohio
Robotic Excavator ("REX") and Autonomous Pipe Mapper	autonomous excavation around buried utility metallic pipes, potentially for several types of autonomous non-destructive testing	Carnegie Mellon University, Pittsburgh, Pennsylvania
"NavLab"	autonomous navigation in unstructured terrain	Carnegie Mellon University, Pittsburgh, Pennsylvania
Remote Work Vehicle	nuclear accident recovery work, demolition of structures after nuclear accidents, structural surface decontamination, cleanup and treatment, transport of materials	Carnegie Mellon University, Pittsburgh, Pennsylvania
"Wallbot," "Blockbot," Shear Stud Welder	construction of building interior partitions with metal track studs, concrete masonry work, welding of shear connections in composite steel/concrete structures	Massachusetts Institute of Technology, Cambridge, Massachusetts
Automated Pipe Manipulator	teleoperated pipe system assembly in industrial processing plants	University of Texas, Austin, Texas
Automatic Pipe Bending System	robotic bending and connection of metallic of pipe sections	University of Texas, Austin, Texas
Experimental Maintenance Device	automated pavement crack sealing	Carnegie Mellon University, Pittsburgh, Pennsylvania

Table 1. Examples of Robotics Developed in the United States

Progress in software and hardware systems development concentrated in the past few years primarily on providing relevant building block components for engineers and operators performing various construction tasks. A variety of commercial products intended to aid construction site engineers and workers in automating some of their routine activities have been introduced. For example, bar-code technology and voice recognition software has been successfully integrated with database programs for construction tool tracking, inventory control, and materials management at Bechtel National, Inc., one of the largest U.S. engineering and construction firms. Bechtel has also used a workstation-based graphic animation package to check for interferences in new three-dimensional (3-D) designs of industrial facilities. This program is also available for personal computer (PC) applications.

"Virtual reality" technology has also been utilized at Bechtel to guide a design engineer through a 3-D image of a structure considered for construction and try many design alternatives in a real-time 3-D session. Additional effects such as gravity of objects in the facility under design and lighting effects have also been implementated in some hardware and software setups. Stone&Webster Engineering Corporation, another large engineering and construction firm, has successfully integrated graphics simulation of construction process performance with computerized project scheduling capability.

Small "notebook" computers offer the computing power equivalent to that of mainframe computers 15 years ago. Although still in experimental stages, "head's up" virtual screen display technology for portable field computers enables the field engineer or superintendent to read blueprints of electrical and piping systems and aid in maintenance planning, monitoring and performance. This technology may, when coupled with appropriate sensory and measurement techniques, enable real time updates of blueprints. Thus, an important problem in many branches of the construction industry, namely the verification of "as designed" with "as built" conditions, has begun to be addressed.

A number of new artificial intelligence (AI) software technologies have been introduced for construction automation decision support. Numerous expert system prototypes have been developed to-date. In particular, neural network applications and machine learning techniques have been introduced for construction site data analysis. Both of these technologies have been areas of active research and are now being considered for practical software implementation projects.

As an example of a recent development, a prototypical construction robotic equipment management system has been developed at Purdue University. It is intended for use by a major engineering and construction firm already in possession of a large fleet of construction robots. The system may assure that the scarce robotic resources are utilized fully to the firm's advantage in order to maximize the economic benefit of their application.

Examples of Current Research

As discussed above, software research and development exceeds hardware design and development in American construction automation activities. A few examples are listed below.

Purdue University is involved in the development of a testbed work cell for robotic material handling on future Automated Building Construction (ABC) sites for high-rise building projects. This testbed work cell utilizes a Mitsubishi *MoveMasterEX* desktop industrial robot, bar-code technology for automatic construction material identification, material storage location, and for recording material usage sequence requirements. The physical layout of the robot work cell is presented in Figure 1.

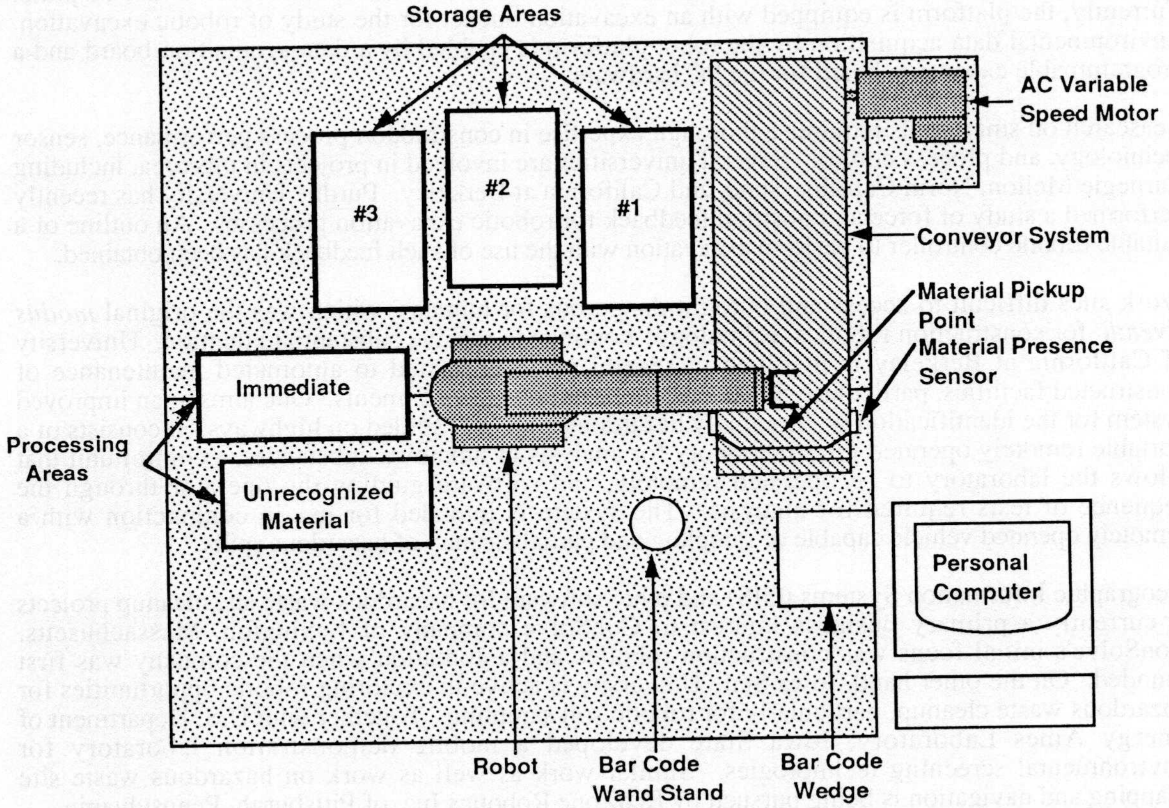

Figure 1. Construction Material Handling Work Cell at Purdue University

University of Texas at Austin has been involved in research on automating critical lift planning technology to lower lifting cost and improve its reliability. It currently focuses on creating algorithms for crane and object location and object lift path planning in 2-D and 3-D environments. Future extensions of these algorithms may include multiple lift planning, crane selection and dynamic control of lifting, as well as automated task and motion planning for construction robotics, including complex spatial and structural interactions. In addition to a pipe manipulator developed in the past, an eight degree of freedom hydraulically powered pipe manipulator is currently serving as a large scale robotics manipulator research platform for work on advancing the control technology developed to-date and for developing multi-functionality technologies.

AI-supported prototype for rebar placement planning in concrete construction has been developed and is undergoing evaluation.at North Carolina State University, allowing the integration of CAD and AI. A feature-based and process oriented framework for design and planning have been developed as a prerequisite for the AI-supported construction process planning system. The prototype has been implemented on a PC with a 386 microprocessor, utilizing "Level-5-Object", "AutoCAD" and "DBase-Plus" software. Plans are being made to integrate design and construction planning of rebar work including fabrication, shipment, on-site storage and control of placement.

A multi-purpose electro-hydraulic robot manipulator platform is undergoing preliminary design phases at North Carolina State. It is intended for several tasks including excavation, welding and lifting of objects on construction sites. The hardware consists of a base, boom, arm with exchangeable tools, strain gages, a load cell, accelerometer and inclinometer and end plate. Currently, the platform is equipped with an excavation bucket for the study of robotic excavation. Environmental data acquisition by the robot platform is enabled by a data acquisition board and a programmable expansion board for the PC hardware.

Reasearch on smart tools requires a thorough expertise in construction process performance, sensor technology, and process control. Several universities are involved in projects in this area, including Carnegie Mellon, North Carolina State, and California at Berkeley. Purdue University has recently performed a study of force and position feedback for robotic excavation processes. An outline of a suitable robotic controller to perform excavation with the use of such feedback has been obtained.

Work sites difficult to access and outright dangerous for humans, which was the original *modus vivendi* for construction robotics technology, continue to receive substantial attention. University of California at Berkeley is involved in several projects related to automated maintenance of constructed facilities, particularly in potentially hazardous environments. One aims at an improved system for the identification of potentially hazardous materials spilled on highways. It consists of a portable remotely operated mini-laboratory for analysis of unknown substances, a control unit that allows the laboratory to be operated remotely, and software guiding the operator through the sequence of tests required for analysis. The system is intended for use in conjunction with a remotely operated vehicle capable of sampling and partial cleanup of hazardous spills.

Geographic Information Systems (GIS) and other software for hazardous waste site cleanup projects is currently a primary business interest to ConSolve company of Lexington, Massachusetts. ConSolve's initial focus was construction robotics and automation when the company was first founded. On the other hand, Iowa State University is active in exploring robotic opportunities for hazardous waste cleanup, particularly for robotic soil sampling. Together with U.S. Department of Energy Ames Laboratory, Iowa State developed a mobile demonstration laboratory for environmental screening technologies. Similar work as well as work on hazardous waste site mapping and navigation is being pursued by RedZone Robotics Inc. of Pittsburgh, Pennsylvania.

Turning to new software development, Purdue University is working on a neural network based, hybrid decision support system for optimizing robotic technology transfer into construction. This project focuses on incremental technological change in robot application scenarios, rather than on a revolutionary change. Another project at Purdue analyzes a possible change in construction project cost escalation due to the selection of a robot as work equipment alternative.

University of Illinois at Urbana-Champaign is currently involved in developing an object-oriented model in "KappaPC" programming environment for integrating design and construction. In this model, relevant design and construction information, as well as construction management knowledge, are represented and integrated. The system allows for scheduling and cost estimating to be automated based on design information, for different scenarios of construction plans to be evaluated from time and cost perspective, as well as for analysis of impact on the cost estimate and construction schedule due to design changes, changes in installation sequence, or changes in construction technology. Other object-oriented computerized project management systems are being developed at Stanford University.

Planning access routes within the construction site is an important item in developing project execution plans. Many project management decisions such as site layout, construction sequence, facility design, and the extent of preassembly are influenced by the need for access. At the University of Texas at Austin, "N-Expert Object" expert system shell combined with "Arc-Info" GIS, "MicroStation" CAD package, and "Excel" spreadsheet program are being used to investigate automated route planning for large vehicles on industrial construction sites.

The Ohio State University is currently active in the automation aspects of construction methods, performance and safety. Visualization and hypermedia have been utilized by integrating animation and expert system technology to establish the construction methods for roads and bridges. Expert system and fuzzy set technology have been used as tools in establishing the extent of damage and repairability of underground structures, foundations and pavements. Fault tree analysis is used to establish the causes of construction and structural failures, the risk of failure, and preventive measures. Also, Northeastern University has been active in research on a decision support system for automatic construction simulation code generation. The initial prototype allows the analyst develop a simulation model in "SLAM" language for truck-loader operation.

U.S. Army Construction Engineering Research Laboratory is interested in information on technologies which can be integrated into construction management tools, particularly for enhancing facilities' constructability through automated construction technologies. In addition, they are pursuing investigations aimed at determining where automated technologies may be instrumental in analyzing construction requirements (i.e., project scope, dimensions, measurements, volumes, etc.) or performing operations for hazardous, toxic, or radiological waste cleanup projects.

Efforts on planning process automation for space construction projects have been underway at the University of Colorado at Boulder, utilizing goal directed planning with topology constraints. The research aimed to develop a decision support system to help a project (mission) planner develop feasible plans. The planner begins by specifying project goals and the system presents, among other recommendations, a list of all project components that would help satisfy this goal. The planning system is integrated with a 3-D solid model CAD system, so the planner can see a visual/graphic representation of a current project task configuration at any time. Current work concentrates of enhancing the system prototype with extensive AI planning capability. Other universities involved in space construction research include Carnegie Mellon, Wisconsin at Madison, North Carolina State, and Texas A&M.

Conclusions

Robotics and automation remain as the most dynamic field of construction engineering research in the United States. However, traditional sources of government funding for this work such as National Science Foundation, National Aeronautics and Space Administration, Department of Defense and others, due to federal and state budgetary constraints, will likely remain insufficient for assuring successful technology transfer. Continuous funding for this endeavor, particularly from the construction industry itself, is necessary to sustain the current pace of new developments in this field. Innovative research financing sources, such as industry research and development tax administered by contractors' organizations, e.g. Associated General Contractors of America or Associated Building Contractors, could be explored. The role of technical committees within professional societies, such as American Society of Civil Engineers' Committee on Field Sensing and Robotics should be supported by the civil engineering profession. Design changes should be permitted by building codes to accommodate the use of robots for construction tasks. Business leaders in the industry may utilize the available construction research expertise in universities and resources such as Construction Industry Institute to initiate new investigations into practical construction robotics implementation strategy throughout the industry.

Industry groups such as Construction Industry Manufacturers' Association should become active in promoting robotics technology among its members. This may contribute to a more rapid growth in construction equipment producers' awareness of new developments in construction robotics, besides forming the necessary synergy with researchers in the field to generate commercially viable construction robotics products.

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