THE CUTTING EDGE IN NORTH AMERICA

Timothy S. Killen - Research & Development
Bechtel Group, Inc.

50 Beale Street
PO Box 3965
San Francisco, CA 94119

ABSTRACT

Automation and robotic applications for use in the North American construction industry are currently under development at numerous university and industry laboratories. A number of these applications have been tested under simulated or actual jobsite conditions; some have provided enough information to determine technical success or economic feasibility of the technology. Further development of robotics applications for the construction industry will be achieved by a combination of university research and development and jobsite experimentation in the private and government sectors.

EARTHWORK APPLICATIONS

Examples of automation and robotic applications on North American jobsites include automated precision guidance systems for construction machinery and remote-controlled devices to inspect or rehabilitate structures. Automated excavation grade control using laser surveying equipment combined with electro-hydraulic feedback control systems mounted on bulldozers, motor graders, scrapers, etc. has been used for civil earthwork applications. In highway grading, large parking lots, and canals, these techniques have reduced costs in some cases by over 80 percent and improved quality (e.g., subgrade thickness tolerances of 2 percent versus 10-20 percent). These methods substitute lower-cost machines (e.g., small bulldozers for motor graders) and lower-skilled operators, while improving quality.[1, 2]

Another earthwork application is the John Deere 690C Teleoperated Remote Controlled Excavator. Fully operable from remote locations, this machine is designed for excavating and handling unexploded ordnance and other hazardous materials such as chemical and nuclear waste. It is equipped with a high-resolution color video monitor with 7-inch diagonal screen, speakers, and amplifiers. The camera controls include pan, tilt, zoom, focus, and iris. The excavator has been used successfully at a munitions disposal site in Tennessee and is being evaluated for rapid runway repair functions.[3]

Other civil earthwork applications include Miller Formless Co.'s Automated Slipforming Systems and Bulk Cement Unloading Systems. [4] Miller Formless has developed five machines for sidewalk curb and gutter construction that can pour concrete closer to obstacles than other forming equipment. They can be assembled to order for the construction of bridge parapet walls, monolithic sidewalks, curbs and gutters, barrier walls, and other continuously formed elements commonly used in road construction. The machines include proportional control of the grade system by two grade sensors; two amplifiers; two servo valves; and a cross-sloping feature. All of these machines can operate in a playback mode, following a preset path of work. These devices require less labor than conventional methods and are considered economically feasible.[5]

Robot Excavator (REX), created by Carnegie-Mellon University (CMU), is another automated earthwork application. REX unearths buried utility piping by sonar-mapping an excavation site, planning the digging operations, and controlling excavation hardware. The REX system integrates sensing, modeling, planning, simulation, and action. Using surface topography and the location of target pipes, it can calculate appropriate trajectories and follow them. REX has the potential to decrease costs and increase productivity for many types of utility excavation, and because explosive gases are sometimes ignited accidentally during blind digging of gas utilities, unmanned excavation can reduce the possibility of human injury and property loss. CMU has successfully demonstrated unmanned, benign excavation in a simulated laboratory excavation using REX.[6]

CMU is also working on automated pipe mapping, developing a system that autonomously establishes the size, depth, and orientation of buried pipes. Primary mapping is completed by a sensor that reads and records magnetic field intensities. These intensities are interpreted and produce a line drawing representing pipe locations. This information is extremely valuable in guiding excavation, validating as-built drawings, and building databases of piping details.[7]

The TERREGATOR machine may be used to transport the autonomous pipe mapping system. Designed by CMU for autonomous, outdoor navigation, TERREGATOR could be directly applied to construction site work.[8] Initial tests have deployed vision for guidance and sonar sensing for mapping. Successful vision navigation experiments have been conducted around the CMU campus; a portion of a coal mine has been successfully mapped and navigated using acoustic range data. TERREGATOR research findings will contribute to the development of other autonomous vehicles in construction, mining, material handling, and military applications.[9]

Boyd Paulson of Stanford University is performing research on the software requirements for robots. To be more effective, robots must have greater intelligence, adaptability, and be more flexible in handling the dynamics of construction jobsites. Paulson is developing a unifying theory and guidelines for defining and communicating this knowledge in a way that can be used by robots. He is developing software-based simulators of the construction environment to test concepts and methods as they evolve. Automated construction robots must be able to deal with uncertainty, adapt to a dynamic environment, seek knowledge beyond their spheres, and work in teams to perform complex tasks. Paulson's objective is to design and develop the general software core for machine agents – the rudimentary "brains" of the beasts – which can then be specialized for particular tasks.[10]

OPERATIONS, CLEANUP, MAINTENANCE, AND DEMOLITION APPLICATIONS

CMU also developed the remote work systems that explored and remedied damage in the crippled Three Mile Island reactor containment basement. The Remote Reconnaissance Vehicle, equipped with a multitude of end-effecters, performed recovery tasks such as inspection, radiological mapping, material sampling, sludge transport, and wall cleaning in a highly radioactive environment. Its successor, the Remote Work Vehicle, was developed for a broad agenda of cleanup operations. The Remote Work Vehicle, with a 23-foot reach, can wash contaminated surfaces, remove sediments, demolish radiation sources, apply surface treatments, and package and transport materials.[11]

The Electric Power Research Institute (EPRI) has been involved in the design, fabrication, assembly, and evaluation of a remotely controlled manipulator called TOMCAT. This machine is used for maintaining and repairing "hot" overhead transmission lines as well as low voltage distribution and underground applications, thereby reducing utility costs. The device consists of a master-slave manipulator; the slave portion of the manipulator is mounted in place of the bucket on an insulated boom truck and is connected via fiber optic link to the ground, where a lineman operates the master unit. A major milestone was achieved in November 1985 at the Philadelphia Electric Company, where TOMCAT was used to remove and replace a string of insulators on a transmission line in simulated energized conditions. EPRI is upgrading the system with plans for full commercialization after its potential is fully developed.[12]

MOOSE, developed by Pentek, Inc., is a remote-controlled six-wheeled chassis that carries a concrete scarifying tool to remove laitance and paint, and clean up concrete slabs. It has an on-board vacuum with waste containment and storage capabilities. This device was used by Bechtel at Three Mile Island and can process 400 square feet of concrete surface per hour.

Faced by a need to visually inspect three 6,000-ft tunnels between the upper and lower reservoirs of its pumped-storage power station in rural Bath County, Virginia, Virginia Power developed a remotely operated diving robot. The HYDROVER is maneuvered by four hydraulic thrusters that can propel it as fast as 90 ft per minute and has a gyrocompass that is not affected by steel tunnel liners and reinforcing. High resolution sonar tracks the vehicle's position and helps plot precisely where leakage occurs. The robot is fitted with cameras that rotate around it to inspect the tunnel and save hours of maneuvering time.[13]

HOIST AND TRANSPORT APPLICATIONS

The National Institute of Standards and Technology (NIST) is presently conducting the Robot Crane Technology Project. The aim is to develop kinematically constrained, dynamically stabilized robot cranes capable of lifting, moving, and positioning heavy loads over large volumes; supporting fabrication tools; and inspecting large and difficult-to-reach structures. Among the objectives are:[14]

- o Achieve a better theoretical understanding of the properties of the proposed crane suspension mechanism, such as stiffness, dynamic stability, etc.

- o Demonstrate the use of the robot crane mechanism for factory automation, such as loading and unloading machines, moving heavy fixtures, etc.

- o Demonstrate the use of the robot crane mechanism for the accurate and efficient positioning of heavy payloads for construction of airplanes, ships, submarines, buildings, dams, bridges, etc.

Progress to date includes the assembly of an intermediate size model robot crane, from which a PUMA-560 robot arm was suspended. A robot tracking laser interferometer was used to monitor the arm movements in three-dimensional space. Also, a three-degrees-of-freedom robot crane payload vibration compensation device was constructed and tested on a small crane model. Considerable development work still needs to be performed.

Caterpillar, Inc., has recently developed the Self Guided Vehicle System, a free-ranging material handling system operating with dead-reckoning and laser guidance. The machine does not depend on a fixed path (such as buried wire). Its design is based on a rugged forklift truck and can be installed and operated in any factory environment where lift trucks can operate. The guidance system works by triangulation from identifiable landmarks that are fixed in known positions within the area of operation. The landmarks are created by installing bar-coded targets at convenient intervals throughout the operating area. Although not specifically designed for construction applications, it could, with some enhancement and modification, perform useful functions at the jobsite.

STRUCTURE, FOUNDATION, ENCLOSURE SKIN, AND INTERIOR FINISH APPLICATIONS

Researchers at MIT are engaged in developing their Integrated Construction Automation Design Methodology (ICADM), focusing on construction of interior wall partitions. Approximately 10 percent of the cost of a commercial office building comes from interior wall construction. The MIT researchers concluded that 20 percent of interior partition construction could be automated. The process of building the interior wall partitions is divided between two separate robots, TRACKBOT and STUDBOT. TRACKBOT, guided by laser beacons, installs upper ceiling and floor tracks. Once it has completed a run of track, STUDBOT can begin placing vertical wall studs. Location is determined by an encoding wheel or electronic distance-measuring instrument. A positioning arm spot-welds studs into fixed position. Based on TRACKBOT and STUDBOT performance, MIT researchers prepared detailed economic studies showing 50 percent savings in labor costs.[15]

The construction of long, one and two-story concrete block walls is a prime candidate for automated assembly. It is a well defined, repetitive task, which is time-consuming, labor-intensive, and potentially dangerous for workers. Recognizing this opportunity for automation, MIT has a project to design, develop, and test BLOCKBOT, a robot for constructing masonry block walls. The wall installation system will consist of:

- o A six-axis head that places blocks on the wall
- o A 20-30 foot hydraulic scissor lift to coarse-position the placement head
- o A large-scale metrology system, sensors, and computer control
- o A block-feeding system/conveyor to supply the placement head

To facilitate construction, the blocks will be dry-stacked without mortar. The wall will then be surface-bonded using Surewall, a commercial fiberglass-reinforced bonding cement.[16]

Since the advent of the stud welding gun, the use of shear connectors in composite steel/concrete construction has gained widespread popularity. With as many as 40,000 studs in one building, the repetitive stud welding process is a fitting application for automation. MIT recently developed STUDMASTER, which automates stud welding on building sites. The device, operated by a construction worker, eliminates the need for the worker to bend over repeatedly, thereby improving efficiency.[17]

MECHANICAL PIPING APPLICATIONS

In 1982, the Business Roundtable released their "Construction Industry Cost Effectiveness Report," stating that piping is the most inefficient and single largest cost element of major industrial construction projects. The report also stated that piping construction is one of three areas with the highest potential for technological advancement.[18]

A multidiscipline team of researchers at the University of Texas at Austin are working on hardware and software development of piping automation for process facilities. The main system component is a Grove Crane and manipulator, provided by DuPont. The researchers have developed an advanced ergo-stick control system for teleoperation of the manipulator. This system provides an intuitive interface for the operator which will significantly increase productivity. The researchers used 3-D graphics simulation with WALKTHRU™ software provided by Bechtel to develop the system. Presently the team is connecting the remote control unit to the Grove manipulator. In June 1989, the combined new controls and the manipulator will be operational and ready for field testing; future research will include:

- Connecting positional instrumentation to the manipulator to determine actual position of arm segment and gripper
- Feeding back positional information to the control unit
- Providing for playback of preplanned sequences of manipulator movement
- Developing path planning and obstacle avoidance algorithms to provide more automatic control of the manipulator

Another device for automated pipe installation is the Big Bolting Tool (BBT) used for placing 90-inch steel pipe underwater. The BBT, manufactured by Constructors Engineering Co., is assembled onto the pipe to be lowered and rides it to the bottom. There BBT aligns the flanges, closes the joint, rotates the joint to align the bolt holes, pushes home the bolts, and torques them up. Once the joint is made, the BBT is released for recovery, ready for the next pipe.[19, 20]

MISCELLANEOUS APPLICATIONS

Although not described in this paper, several other research and development activities in construction automation should be noted: Odetics, Inc., Anaheim, CA, has developed an advanced six-legged robot equipped with 3-D laser imaging radar vision and manipulator assembly; ConSolve, Wayland, MA, is developing "Integrated Automation for Earthmoving" which includes CAE software, precision measurement technology, and microprocessor-based machine controllers for construction equipment; the University of Maryland has studied automated fabrication of stone shapes and developed a prototype stone-cutting robot[21]; the U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, has developed their Real-time Weld Quality Control System; The Robotics Laboratory, Stanford University, is developing schemes for robot motion planning with projects in the area of pipe installation[22]; Virginia Polytechnic Institute and State University has developed the Automated Position and Control (APAC) system to provide real time equipment position data to jobsite personnel[23]; Lehigh University is designing new structural steel connections that can be easily installed by smart tools[24]; and the University of California, Berkeley is using AI techniques for automated construction schedule analysis and evaluation[25].

Finally, there are untold developing applications of engineering automation, CAD/CAE, and expert systems to the construction industry. In one notable development CMU has created an advanced prototype for the integrated design and construction planning of buildings. This system, Integrated Building Design Environment (IBDE), includes seven independent but cooperating knowledge-based systems that can automatically produce designs, drawings, analysis, structural systems, architectural plans, bills of materials, and construction plans. The system is additionally equipped with knowledge-based critics that evaluate the results.[26]

SUMMARY

R&D efforts in automation and robotics are easier to point to than practical jobsite application of robotics. There are many explanations for slow jobsite applications. The pragmatism of our industry (and indeed, society) emphasizes proven methods. Generally, we want quick payback, proven methodology and applications, no risk, and practical/workable technology. Our engineers and constructors are under pressure to meet tighter budgets and quicker schedules. Until now, we have been unable to demonstrate the cost-effective, technical feasibility of robots. The jobsite is a difficult and demanding environment for robotic technology.

However, technology development now permits commercial application. In his new book *Robotics in Civil Engineering*, Professor M. Skibniewski of Purdue has identified several repetitive tasks that could be automated with off-the-shelf technology. He also presents cost-benefit analyses for these applications.[27] Additionally, demand-side needs such as cleanup of contaminated sites, toxic waste handling, work in hazardous environments, and structure rehabilitation will probably drive new developments of automated equipment, leading to successful practical and economic applications of robotics to traditional construction tasks.

The construction industry is striving for enhanced productivity and improved quality. As demonstrated in other industries, robotics and automation will be key to achieving new engineering and construction goals in productivity and quality. The challenges are major – e.g., robot mobility, advanced sensing, new end effecters, smart control systems, hardware weight, workforce training, etc. We do not expect revolutionary employment of robotic solutions in construction, but rather steady progress supported by university R&D resources with industry support and experimentation at project jobsites.

ACKNOWLEDGEMENTS

Several individuals have provided invaluable assistance in the development of this paper. I wish to acknowledge the special contributions of:

Laura Demsetz, MIT
Jim O'Connor, University of Texas
Mirek Skibniewski, Purdue University
Boyd Paulson, Stanford University

Also, I acknowledge the exceptional support of my Construction Technologies Staff including Reed Nielsen, John Robinson, Chris Snow, and Mike Williams.

REFERENCES

[1] For further information, contact Spectra Physics; Gradeway Construction Company; Agtek Development Company, Inc.; CLS Industries, Inc., and Laser Alignment, Inc.

[2] Paulson, Boyd C., "Automation and Robotics for Construction," *Journal of Construction Engineering and Management*, Vol. 111, No. 3, September 1985

[3] Deere and Company, Government Products Operations, Moline, IL

[4] Miller Formless Co., Inc., McHenry, IL

[5] Skibniewski, Dr. Miroslaw J. and Russell, Dr. Jeffrey S., "Technology Transfer to Construction: Advanced Robotics," *Cost Engineering*, American Association of Cost Engineers, 1989

[6] Whittaker, W.L., Carnegie-Mellon University, "REX: A Robotic Excavator," August 1985

[7] Skibniewski, M.J., Purdue University, "Construction Robotics: State of the Art in the United States of America," prepared for Byggecentrum, Copenhagen, Denmark, December 1988

[8] *ibid.*

[9] Whittaker, W.L., "Terregator," Carnegie-Mellon University, The Robotics Institute, August 1985

[10] Paulson Jr., Boyd, Babar, Nadeem, Chua, Lai-Heng, Froese, Thomas, Stanford University, "Simulating Construction Robot Agents and Their Knowledge Environment," CIFE Working Paper No. 003

[11] Whittaker, W.L., Carnegie-Mellon University, "The Remote Work Vehicle," July 1986

[12] *EPRI Journal*, July/August 1987, page 15

[13] *ENR*, February 9, 1989, "Diving robot saves a utility millions," page 17

[14] Dagalakis, N.G., Albus, J.S., Goodwin, K., Lee, J., Tsai, T., Abrishamian, H., Bostelman, R., "Progress Report of the Robot Crane Technology Program," National Engineering Laboratory, National Institute of Standards and Technology, December 1988

[15] Skibniewski, M.J., Purdue University, *op. cit.*

[16] Skibniewski, M.J., Purdue University, *op. cit.*

[17] Demsetz, Laura, Massachusetts Institute of Technology, "Current Work in Construction Automation," Part 1-Automated Equipment, February, 1989

[18] Fisher, Deborah J., University of Texas, "Piping Erection Constructability Issues in a Semi-Automated Environment," 1989

[19] ENR, June 16, 1988, "Firm tailors equipment to needs," page 33

[20] Lively, T.W. et al, "Construction of the Iona Outfall - Submarine Section," 1988 Annual Conference, Canadian Society for Civil Engineering, May 25, 1988

[21] Livingston, E. and Bernold, L., University of Maryland, "Enhancing the Civil Engineering Education Experience Through the Use of Expert Systems and Robotics," 1988 Annual Conference of the American Society of Engineering Education, June 1988.

[22] Latombe, Jean-Claude, Stanford University, "Robot Motion Planning," CIFE Symposium, March 1989

[23] Beliveau, Y.J. VPI, "Global Data Base for an Automated Construction Industry," *Civil Engineering in the 21st Century*, ASCE, November 1987

[24] Fenves, S.J. et al, Carnegie-Mellon University, "A Prototype Environment for Integrated Design and Construction Planning of Buildings," CIFE Symposium, Stanford University, March 26, 1989

[25] Skibniewski, J., Purdue University, *Robotics in Civil Engineering*, Van Nostrand Reinhold, 1988

[26] ATLSS B2 Project Summary "Construction Automation," ATLSS Report No. 88-02, March 1988

[27] C. William Ibbs, UC-Berkeley, "Automated Construction Schedule Analysis and Evaluation," 13th Congress of the International Association of Bridge and Structural Engineering, Helsinki, Finland, June 1988