Automated Construction?

Manufacturing has become highly automated — so why not building construction?

Take a look at the products you use every day. Telephones, personal computers, the soft drink you had with lunch—each was probably manufactured in a highly automated facility. Fixed automation and, more recently, flexible automation and robotics, have greatly reduced the cost of many manufactured products by reducing labor requirements, increasing the speed of production, and, in many cases, improving quality and safety.

Now look at the building in which you live or work. While many of the components that make up this building may have been manufactured in automated facilities, the building itself was most likely assembled (constructed) using a great deal of manual labor. Could the construction industry reap some of the benefits of automation that have been seen in manufacturing? Many people, both in the U.S. and abroad, think the answer is yes.

Terminology

The last decade has seen increased interest in exploring the potential uses of automation in construction. Before examining the reasons for and results of this interest, it is appropriate to review some terminology.

Automation has been defined in general terms as the replacement of human labor by machinery. A more specific definition in manufacturing would be “a system or method in which many or all of the processes of production movement and inspection of pans and materials are automatically performed or controlled by self-operating machinery, electronic devices, etc.” (Webster’s Dictionary). The more general interpretation of automation will be used here, as it encompasses both automatically and remotely controlled devices.

This article focuses on automation of the physical aspects of construction processes. However, the term automation is also used with reference to information processing. In construction, this type of automation is evidenced in such activities as computer-aided design and drafting, and the use of computers for estimating, scheduling, and accounting.

Automated systems are frequently classified according to the ease with which they can be adapted to meet changing demands. Fixed automation, the sequence of operation is determined by the configuration of the system. Fixed automation has been used for many years; a commonly cited early example is Jacquard’s early nineteenth-century mechanical loom, which was controlled by punch cards. Today, much of the production of high-volume items is accomplished with the use of at least some fixed automation.

Systems in which operations are modified based on input from sensors are referred to as intelligent or adaptive automation. Among current topics of research in manufacturing are the improved real-time monitoring of processes (particularly tool wear) and the use of artificial intelligence to interpret sensor output and modify operations accordingly.

The current research in construction automation is frequently described as construction robotics. In the U.S., an accepted definition of a robot is a “reprogrammable multi-functional manipulator designed to move material, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks.”

In some systems, known as teach-playback robots, reprogramming is...
accomplished by moving the manipulator once through the required sequence of motion. The system automatically generates the instructions necessary to repeat the sequence. In other robots, programming from a keyboard is possible. As with other types of automation, robots for which operation can be modified based on sensor input are referred to as adaptive or intelligent.

In Japan, a broader interpretation of a robot has been adopted. It incorporates teleoperated devices—devices that are controlled remotely by an operator rather than through a preprogrammed series of commands. Much of the work that has been referred to as construction robotics has actually concerned teleoperated machines. To avoid confusion, the more general term construction automation will be used here.

**Benefits of Automation**

What are the potential benefits of automation in the construction industry? The benefits are likely to be similar, though not identical, to the benefits of automation in manufacturing. These commonly include reduced labor requirements, increased speed of production, improved quality, improved safety, reduced inventory, stabilization of work-force requirements, reduction in scrap, and improvement of company image.

Labor remains a large component of the overall cost of a construction project. Construction labor is expensive; hourly wages are higher than those in most industries. In spite of this, there is some concern over potential labor shortages, with the difficulty in attracting new workers attributed to a post-baby boom reduction in the number of entry-level employees, and to the physically demanding nature of the work.

Reduced labor requirements in construction could therefore be an important benefit of automation.

Automation could improve the use of another construction resource—time. Time is critical in construction; the importance of finishing a job quickly is reflected in the use of bonuses for early and penalties for late completion. Even if labor costs remained constant an automated system that resulted in increased speed of construction could be beneficial.

Following the lead of successful Japanese competitors, many manufacturing firms in the U.S. have begun to view improved quality throughout the manufacturing process as a way to improve overall productivity. While it has been noted that in construction “quality is generally considered quite acceptable, if skilled craftsmen are available and conformance standards are defined,” a shortage of skilled craftsmen and inspectors would make it difficult to maintain construction quality. Automation could help maintain consistent output over long periods of time. Furthermore, the automation of inspection could help reduce delays caused by a shortage of inspectors. The result would be improved quality in construction.

Finally, a major benefit of automation could be improved safety in construction. Construction remains one of the most hazardous ways to earn a living. It has been estimated that over six percent of total project costs are due to construction accidents. Automated machines could limit the need for people to work in hazardous environments. Increased use of machines for tasks requiring repetitive motion could help reduce the incidence of cumulative trauma disorder—an increasingly significant cause of workman’s compensation claims and OSHA fines. In addition to improving productivity through a reduction in the rate of injury, improved construction safety could make the industry more appealing to a shrinking labor supply.

Because construction is a project-based industry subject to large fluctuations in demand, such factors as reduced inventory and stabilization of work-force requirements are likely to be of less importance than they have been in manufacturing. Reduction in scrap is also likely to have a relatively small effect. The use of automated equipment could affect company image, but, at least in the U.S., the impact is likely to be small relative to items that directly affect the cost of a project. Reducing labor requirements, increasing speed, improving quality, and increasing safety thus appear to be the most important ways in which automation could improve construction productivity.

**Obstacles to Automation**

The most serious obstacle to automation in construction is the complex and changing environment of the construction site. The physical characteristics of the site vary from day to day. Even the cleanest and neatest of sites appears quite disorderly when compared with a typical automated manufacturing facility. Tools, material, and debris clutter the workplace; obstacles are found at different locations each day. A machine that could autonomously navigate even one floor of a typical building while mechanical systems were being installed would require sophisticated sensing and path planning abilities.

There are two main approaches to dealing with the construction site environment. The first is avoidance: move as many of the processes as possible to an environment that more closely resembles a factory, and then apply the types of automation that have been successful in the factory environment. Examples of this approach are given in the section on prefabrication. The second approach is to focus on partial automation, where the construction
worker remains a vital part of the process. Most of the so-called construction robots developed to date rely upon human operators for both initial positioning and for control during operation. This can help overcome a second major obstacle to automation: resistance from labor.

Labor in many industries has traditionally been wary of attempts to increase productivity through automation. A recent study by the National Academy of Sciences’ Panel on Technology and Employment concluded that “reductions in labor requirements per unit of output resulting from new process technologies have been and will continue to be outweighed by the beneficial employment effects of the expansion in total output that generally occurs.” However, these benefits accrue to society as a whole, not necessarily to those displaced by a new technology. Workers and their unions continue to fear that automation will result in a decrease in employment opportunities, a deskill- ing of remaining jobs, and a decline in wages.

Can construction reap the benefits of automation?

Keeping the human “in the loop” can help alleviate some of these fears. Automation becomes a means of providing a worker a better tool, rather than a way to replace a man with a machine. Machines can be designed for strength, speed, and repeatability. But man is unsurpassed in intelligence, judgment, and the ability to adapt to changing surrounding. Interviews with construction foremen indicate that workers find repetitive tasks boring and unpleasant, and seem most appreciative of equipment that reduces the physical demands of construction work.”This is especially true of older workers. Those aspects of construction work that craftsmen seem to like least are often those best suited to automation. In light of anticipated labor shortages and the increase in the average age of the construction work force, opposition to automation may not be as strong as feared. Two other factors sometimes mentioned as obstacles to automation are the high anticipated cost of automated equipment and the diffi-
Off-Site Automation

The use of automation in manufacturing has been critical in allowing goods to be produced economically. In spite of recent trends towards flexible automation, most applications of automation thus far have been to repetitive tasks in well-controlled environments. In the typical manufacturing facility, temperature, humidity, and lighting are maintained at levels suitable to the type of work being done. The layout of the plant does not vary from day to day. The work force, too, is relatively stable over time. Workstations, whether manual or automatic, are usually stationary, with the product moved from location to location as necessary in the course of production. Production machinery can generally be much larger than the product, simplifying the design of an accurate, repeatable system.

In contrast, construction is carried out in an environment that is anything but constant. The day-to-day variation in the physical characteristics of a construction site, the changing composition of the work force throughout a job and from one job to the next, and the necessity for workers and equipment to move around a large stationery product and from project to project present obstacles to the use of equipment and techniques that have been successfully applied in manufacturing. One way to avoid these obstacles is to carry out construction tasks in an environment similar to that found in manufacturing. Not surprisingly, some of the most successful examples of automation in construction occur off-site, either in the processing of construction materials, or in the prefabrication of construction components.

Material Processing. The production of most construction materials has been automated to a large extent. Steel mills and sawmills have traditionally been highly automated. Concrete batch processing plants and many precast facilities have been at least partially automated. The manufacture of products such as plywood and gypsum wallboard is highly automated. A 16,000-square-foot, fully automatic concrete block manufacturing plant in West Germany requires only one man to oversee production. In the manufacture of these and other construction components, large quantities of a product are produced at a permanently located plant. There is little resemblance to the type of work carried out on a construction site.

Prefabrication. Prefabrication in construction is an attempt to improve productivity by carrying out selected operations in a more controlled environment. Assemblies can be prefabricated either on the site (but at a location removed from the installation point) or off-site. In some cases, work in a prefabrication facility proceeds much as it would on a construction site. For example, in the construction of commercial buildings, plumbing trees are often prefabricated manually in an on-site workshop. The workshop provides shelter from the elements, permits assemblies with the same configuration to be produced at the same time, and reduces the need for welding at diverse locations through-out the project.

Often, however, the prefabrication process is automated to some degree. Robots have been used to automate stud welding in the prefabrication of reinforcing plates for heavy facilities. An automated masonry system allows block walls to be prefabricated adjacent to a construction site, while a crane is used to move the wall sections into place. Automation of a prefabrication process off-site can be seen in the manufacture of wood trusses and floor decks. In Japan, 45 percent of housing is prefabricated units produced in highly automated factories. When the prefabrication of a construction assembly has been automated, it has been through a system in which the machinery of automation is larger than the part being worked on; the situation is similar to that in a manufacturing facility.

On-Site Automation

While prefabrication off-site has been successful for some aspects of construction, most work is still carried out on-site by workers with the aid of tools and equipment. During the past 10 years, the on-site automation of construction processes has received a great deal of attention.

Three factors appear to be responsible for this interest. The large Japanese construction companies felt a need to make construction work safer and less labor intensive in light of feared labor shortages, and began substantial R&D programs in the area of construction automation. In the U.S., the 1979 accident at the Three Mile Island nuclear plant created an immediate need for inspection, sampling, and demolition work in an extremely hazardous environment. This led to the development of a series of machines at Carnegie Mellon University (CMU), which established CMU as an early U.S. leader in construction automation and kindled interest at other universities as well. Finally, worldwide concerns about productivity in construction along with perceived productivity improve-
ments due to the introduction of robots in manufacturing, generated interest in the use of robots on construction sites.

For on-site automation of construction processes to be successful, technical feasibility is not enough; automated equipment must be economically feasible. In terms of economic feasibility, it is useful to differentiate between hazardous environments and typical environments. In hazardous environments, the value of increased safety is such that even if the cost of an automated system is much higher than the cost of current practice, the automated system may be economically feasible.

**Automation in Hazardous Environments.** In hazardous environments, the risk to human life is so great that virtually any expense can be justified in pursuit of an alternative. Such a situation existed following the accident at the Three Mile Island Reactor where “the TMI-2 reactor flooded the containment building basement with several feet of radioactive-contaminated river water. . . [and] radiation levels [precluded] human entry. . .” The Remote Reconnaissance Vehicle (RRV), the Remote Core Sampler (RCS), and the Remote Work Vehicle (RWV) were developed at Carnegie Mellon University in response to a clear need to keep humans out of contaminated areas during the reactor clean up. These machines are teleoperated, with feedback to the operator provided through video cameras and other sensors. Power is supplied through an umbilical cable, so that a compromise between fuel weight and length of mission is not required. Because of the harsh conditions inside the reactor building, the machines are ruggedly designed. The RRV was used in the TMI-2 building in 1984; the building was found to contain tons of sediment, debris, and contaminated equipment and material. This information was used in planning the core sampling program carried out with the RCS. The RWV was designed to be the workhorse of the series, carrying out demolition and recovery work.\(^{14}\)

---

**Production of building materials is largely automated.**

Many other devices have been developed for use in radioactive environments. In most, the operator controls the device remotely with visual feedback provided via video cameras. However, with the DSCR, a diamond sawing/coring unit for reactor dismantling developed by the Japan Atomic Energy Research Institute (JAERI) and Shimizu Corporation, gross movements are controlled remotely, while cutting speed and fine point-to-point movements can be preprogrammed.\(^{15}\)

Demolition can be hazardous even when radiation is not involved. Following the collapse of Oakland’s Cypress Street viaduct in the October 17 Loma Prieta earthquake, a remotely controlled pavement breaker was brought in to help cut through the upper deck. The breaker was originally developed for work in a radioactive environment. It was used at the freeway collapse because it is remotely controllable and lightweight; the freeway section had not yet been shored.\(^{16}\) The device is one of several remotely controlled demolition tools that are commercially available.

Armed combat is certainly a hazardous environment. Even in training, there are situations in which human life is at risk. A remotely controlled excavator developed by John Deere has been used in several such applications. Based on the John Deere 690 Excavator, it has been used to excavate and recover unexploded munitions for testing and to provide soil samples for analysis of possible contamination. A
modified version is currently being tested for use in rapid runway repair.

The ocean is another potentially hazardous environment. Undersea construction and inspection has been facilitated by manipulators controlled remotely from within minisubs and by devices teleoperated from the surface. Virginia Power recently developed a teleoperated unit called the Hydorver to inspect 6,000-foot-long tunnels at a power station. The Hydorver is equipped with cameras and a dye release system to help identify leaks.

The “final frontier” is perhaps the final word in hazardous environments. Construction in space is a prime target for automation; the field has attracted several major construction companies as well as traditional aerospace concerns. Space is not only a dangerous site for construction work, but a costly location to which to send equipment as well. A space construction machine will almost surely have to be multifunctional to justify its existence as payload. Martin Marietta Space Systems is currently developing the Flight Telerobotic Servicer (FTS), a “one-legged, two-armed robot with ‘eyes’ on its wrists.” The FTS will provide both visual and kinesthetic feedback; through the control interface, the operator will be able to “feel” the forces exerted by the arms. The FTS is a telerobot, a teleoperated machine capable of limited autonomous function. An eventual goal is to use artificial intelligence to increase the extent of autonomous function.

**Automation in Typical Environments.** In typical construction environments, automated equipment must compete with current practice. Only if the benefits of automation exceed the purchase, operation, and maintenance costs will automation be successful.

The most significant commercial successes thus far have been in the partial automation of existing heavy equipment. The best-known example is undoubtedly the laser-based system for grading. A sensor mounted on the blade responds to a rotating laser beacon and accurately feeds back blade height to an automatic blade control system and/or a human operator. The use of these systems has reduced grading costs by as much as 75 percent, improved tolerances, and allowed the use of less-costly equipment and less-skilled labor. Additional examples include vibratory rollers that automatically measure the load-bearing capacity of soil during compaction and signal the operator when a desired degree of compaction is reached; excavator control systems that maintain constant bucket angle regardless of boom and arm movements; and hydraulic rock breakers that automatically adjust energy per blow and blow rate to accommodate variations in soil type.

A wide variety of new machines that automate or partially automate various construction tasks has been developed in recent years. Some have been used on a number of construction sites; others are still in a laboratory prototype phase. Several of these devices are described in the following paragraphs. While this review is by no means complete, it is representative of work to date.

**Excavation.** A modified excavator developed by Tokyu Construction Company reduces the number of separate pieces of equipment required. The addition of a detachable gripper below the bucket allows the same machine to serve both functions. A further modification—the addition of a movable platform on the front of the crawler unit—allows transport of concrete blocks from the delivery vehicle to the point of installation. The excavator and gripper can be operated from the cab or via a remote control console.

**Concrete Placement.** The Horizontal Concrete Distributor (HCD) was
developed by Takenaka Corporation to reduce manpower requirements and minimize rebar disturbance during concrete pours in building construction. The HCD, which weighs approximately four tons, consists of a four-link arm that clamps to one of the building’s steel columns and supports a concrete-placement hose. The arm moves parallel to the floor being poured, and can cover an area of approximately 1000m². The original version of the HCD was manually controlled; the operator sat in a cockpit mounted to the outer link of the arm and “drove” the unit through the work area. A more recent version incorporates automatic nozzle positioning and automatic obstacle detection. The automatic system was found effective in locations with limited work space and numerous obstacles; the manual system is still used in areas where movement is less complicated. 

Concrete finishing. Several of the large Japanese contractors have developed teleoperated systems for concrete finishing work. Shimizu Corporation’s FLATKN, for example, is powered by an onboard generator and operated by remote radio control. FLATKN has been used on several construction sites, and is said to reduce labor by a factor of four or five as compared with manual trowelling. The Construction Industry Institute is currently testing and evaluating a FLATKN unit.

Rebar placement. Both Takenaka Corporation and Kajima Corporation have developed automated cranes for placement of heavy rebar. The cranes can be teleoperated or run in teach-playback mode. Both units perform placing functions only; the rebar is tied by hand. Masonry. Masonry may at first glance seem an ideal task to automate because it requires the repetitive placement of parts and is a potentially dangerous task for worker (due to falls and the effects of repetitive motion). However, automation of the process as it is currently carried out is extremely difficult. Increased rates of production are constrained by the setting time of mortar. The metrology problem is significant: if each block is out of alignment just a bit, the wall will be uneven and perhaps unstable. Several systems have been developed to automate masonry work, though none has yet been used effectively on a construction site. Most rely upon changes in the materials and method of masonry to facilitate automation. For example, the Blockbot, designed at the Massachusetts Institute of Technology, is designed to stack precision-ground cement blocks without mortar, and then apply a bonding cement to the wall face. A partial prototype of the Blockbot has been developed; the most likely application for this type of machine is in the construction of long continuous walls (for example, sound abatement walls along freeways).

Structural Steel. Shimizu’s Mighty Jack is used for the temporary positioning of steel beams. While holding a beam, the unit is hoisted to the top of the two columns to which the beam is to be attached. Mighty Jack’s grippers grab the columns and position the beam between them. The crane cable is then detached via remote control. After the beams have been fastened to the columns, the crane retrieves Mighty Jack. An ongoing topic of research is the incorporation of fastening capabilities into Mighty Jack. The success of this will no doubt hinge upon the extent to which the design of the beam column joint can be standardized.

Shear studs. The Studmaster, developed at the Massachusetts Institute of Technology, automates the placing and welding of shear studs in composite deck construction. The motivation for the machine came from discussions with welders who complained the repeated bending required to use a standard weld gun made for sore backs. The Studmaster automatically positions a shear stud and ferrule, and welds the stud to the deck. The unit is approximately the size of a lawn-mower. In the current version, the operator rolls the Studmaster to the position where a stud is to be welded, and initiates the welding sequence by toggling a switch. The prototype version was tested on a building site, and worked well enough to generate an equipment manufacturer’s interest in further development.

Fireproofing. Shimizu’s SSR fireproofing unit was one of the first construction robots developed. Currently in its third generation, the SSR sprays rockwool on structural steel. The motivation for its development was the unpleasant working conditions that accompany manual spraying operations. Many improvements have been made over the initial version of the unit; the SSR-3 is a true construction robot. It can be preprogrammed with the layout of a floor and the location of cutouts in beams. During operation, the SSR-3 uses sensor feedback along with the preprogrammed layout to adjust spray position. The SSR-3 has been used on several construction sites.

Exterior finishing and inspection. Several companies have produced devices for finishing and inspecting exterior surfaces of buildings. For example, Taisei Corporation has developed a two-unit system for painting the exterior of high-rise buildings. The power supply, controller, and paint supply move along tracks mounted on the buildings roof. The painting module is suspended by cables from the main unit, and is guided by vertical grooves incorporated into the exterior of the building. The module can recognize windows and change the painting pattern to avoid them. As with other forms of building-mounted scaffolding, the building must be designed with the use of the painting system in mind.

Interior finishing. Both Taisei and Shimizu have developed machines.
to assist in the installation of wallboard. Taisei’s Wall-board Manipulator is essentially a power-assisted lift, supporting a board so that the operator can easily guide it into position. Shimizu’s CRF-1 raises and positions a ceiling panel. A step mounted on the base of the machine enables a worker to fasten the board to the ceiling without scaffolding.

Pipe installation. A remote-controlled pipe manipulator developed by Grove Manufacturing Company for Du Pont is currently being modified at the University of Texas at Austin. Previously, an operator controlled the device through a series of control levers. Because this control system proved difficult to use, a more ergonomic interface is being developed. The levers have been replaced by the “ergostick” a device that translates motions at the operator’s hands, elbows, and wrists into motion of the pipe manipulator’s eight axes. Initial testing indicates that the ergostick does increase the ease with which the pipe manipulator can be controlled.

Automation in the Future
How will automation affect construction work in the years to come? Some envision a fully automated “construction site of the future” at which work is carried out by a fleet of autonomous machines. However, this does not seem to be a realistic scenario. Even in hazardous environments, where a more expensive automated system could be justified, human intelligence will remain a valuable commodity. Teleoperated equipment that enables a person to exercise judgment from a safer location will continue to be used. While more-advanced telerobotic systems will autonomously control many of the details of the machine’s function, overall control of the operation will likely remain the domain of a human operator.

Changes in the construction work force will affect the introduction of automation. As the average age of the work force increases, there will be a greater demand for equipment that frees the construction worker from physically demanding tasks. The projected shortage of skilled construction labor will increase the importance of equipment that automatically monitors and inspects work in progress. Partially automated heavy equipment has already proved useful in this respect. The applica-
tion of similar technology to smaller equipment and power tools will lead to “smart tools” that could reduce the need for rework by automatically performing inspection functions at the time of installation. The incorporation of information storage capabilities will allow smart tools to support project control and documentation as well.

Some of the machines described in this article may eventually become commonplace. Others will come into use after additional refinement and redesign. For some construction tasks, automation may never be an economically viable alternative. For many, automation will make sense only on certain jobs. As an analogy, consider the number of ways a hole can be made in a piece of material—with a hammer and punch, a hand drill, a power drill, a drill press, a milling machine, a CNC milling machine, or a flexible machine center. All of these are currently used; the existence of more highly automated systems has not made simple hand tools obsolete. The appropriate choice for a particular job depends on physical characteristics and on economic factors.

In construction, automation will have the greatest impact when designers, material suppliers, equipment suppliers, construction management, and construction labor work together to ensure an appropriate choice of technology for a particular job.

For More Information

Information on commercially available equipment can be obtained from manufacturers. To find out more about automated equipment under development, see the proceedings of the annual International Symposium on Automation and Robotics in Construction (ISARC). The fifth ISARC was held in Tokyo in 1988; the sixth, sponsored by the Construction Industry Institute, was held in San Francisco in 1989. This
June, the seventh ISARC will be held in Bristol, England.

NOTES

1. For a review of the uses of computers in construction, see the June 1989 issue of The Construction Specifier.


3. See, for example, “Industry is divided over whether craft shortages will be wrenching.” ENR, October 20, 1988.


5. Ibid

6. These are currently a topic of research interest (for example, the NavLab project at Carnegie Mellon University), but are not yet ready for production use.


10. Kajima Corporation, Tokyo, company literature.


14. Ibid.


34. Taisei Corporation, company literature.


37. For more information, contact The Secretariat, Seventh International Symposium, J&M Conferences, P.O. Box 1064, Thornbury, Bristol BS12 2QB, England.

This article is reprinted by permission from the January 1990 edition of The Construction Specifier.

ABOUT THE AUTHOR...

Laura Demsetz, Ph.D., is an assistant professor in the Department of Civil Engineering at the University of California, Berkeley. Her research interests include construction automation, smart tools, and human factors.