

# 6

## Construction Automation

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### 6.1 Introduction

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In the U.S., the construction industry is one of the largest industrial sectors. The expenditure on construction between 1996 and 1999 was estimated at \$416.4 billion dollars, which amounts to about 4.5% of the U.S. Gross Domestic Product (GDP) [Lum and Moyer, 2000]. The construction industry's share increased from 4 to 4.5% between 1996 and 1999. In addition, over 6.8 million people are employed in the construction industry, including design, construction, remodeling, maintenance, and equipment and materials suppliers. This number represents 5.2% of the nonagricultural labor force of the U.S. [BLS, 2001]. Clearly, this enormous capital investment and expenditure and large number of employees highlight the crucial role that the construction industry plays to enhance the overall national economy of the U.S.

Despite its importance to the national economy, the U.S. construction industry faces a number of problems in safety, quality, productivity, technology, and foreign competition. To overcome these problems, automation and robotic technologies are often considered solutions [Everett and Saito, 1996; Cousineau and Miura, 1998; Warszawski and Navon, 1998]. Since 1980, significant efforts have been made to introduce automation and robotic technologies into construction. However, only specialized applications of automation and robotics have been implemented due to economic and technical considerations.

In many cases, the work site poses a significant health hazard to humans involved. Hazards are associated with work in undersea areas, underground, at high elevations, on chemically or radioactively

contaminated sites, and in regions with prevailing harsh temperatures. The U.S. construction industry continues to be the industrial sector responsible for the most occupational accidents, injuries, and fatalities. Hinze [1997] mentioned that the construction sector has generally accounted for nearly 20% of all industry worker deaths. There were 1190 fatal occupational injuries and 501,400 nonfatal injuries and illnesses in construction in 1999. Incidence rates for nonfatal injuries and illnesses were 8.6 per 100 full-time equivalent workers in construction and 6.3 per 100 full-time equivalent workers in all private industry. The accidents in the construction industry alone cost over \$17 billion annually [Levitt and Samelson, 1993; BLS, 2000a, b]. Even though the incidence of injuries and fatalities has reduced by about 50% during the last three decades, the number of accidents, injuries, and deaths remains high when compared to other industries [Smallwood and Haupt, 2000]. Consequently, liability insurance for most types of construction work is costly. Replacing humans with robots for dangerous construction tasks can contribute to the reduction of these costs.

Decline in construction productivity has been reported by many studies conducted throughout the world. In the U.S., construction productivity, defined as gross product originating per person-hour in the construction industry, has shown an average annual net decrease of nearly 1.7% since 1969. The average of all industries for the same period has been a net annual increase of 0.9%, while the manufacturing industry has posted an increase of 1.7% [Groover et al., 1989]. The Bureau of Labor Statistics' (BLS) productivity index also shows the declining tendency of construction productivity. This decline in construction productivity is a matter of global concern, because of its impact on the economy's health. Recent trends have made availability of capital and innovation through the application of automated technologies the defining parameters of competitiveness in today's global economy. These trends enable projects to be constructed with improved quality, shorter construction schedules, increased site safety, and lower construction costs.

Much of the increase in productivity in the manufacturing industry can be attributed to the development and application of automated manufacturing technologies. This, combined with concern about declining construction productivity, has motivated many industry professionals and researchers to investigate the application of automation technology to construction. As a practical matter, these efforts have recognized that complete automation of construction works is not presently technically and economically feasible. Because of frequently reconfigured operations, often under severe environmental conditions, the construction industry has been slower than the manufacturing industry to adopt automation technology [Paulson, 1985].

Tucker [1990] mentioned that complaints of poor construction quality have long been traditional in the U.S. construction industry. Quality is defined as the conformance to requirements that are described in contract documents such as specifications. To meet requirements, things should be done right the first time, and rework should be avoided. Nonconformance will result in extra cost and project delay. There are several major barriers to successful quality work, such as lack of skilled workers, poorly installed equipment, poor plans and specifications, poorly defined work scope, etc. Among them, the skilled worker shortage problem is most critical. Many industrial nations, including Japan, France, Germany, and to some extent the U.S., suffer from a shortage of skilled construction labor. This trend of worker shortages in many traditional construction trades will most likely continue into the future. This will result, as it has over the past two decades, in an increase in the real cost of construction labor. These facts, together with the rapid advancement in automation and robotics technology, indicate promising potential for gradual automation and robotization of construction work.

Many experts stress that the future success of the construction industry may depend on the widespread implementation of advanced technologies. However, the construction industry is among the least advanced industries in the use of advanced technologies available for the performance of industrial processes and has lagged behind the manufacturing industry in technological improvement, innovation, and adoption. The physical nature of any construction project is a primary obstacle to meaningful work automation. In batch manufacturing, the work object is mobile though the production facility, and work tools can be stationary. The manufacturing industry is similar in size to construction, is better coordinated, and is controlled by larger corporations with in-house management, planning, design, and production

capabilities [Sanvido and Medeiros, 1990]. By contrast, in construction, the “work object” is stationary, of large dimensions, and constantly changing as work progresses, while tools are mobile, whether handheld or mechanized. In addition, construction processes are usually performed in dusty and noisy environments, preventing the use of fragile, high-precision, and sensitive electronic devices. Most construction jobs require a certain amount of on-site judgment, which automated equipment or robots cannot provide. In addition, there are many uncontrolled environmental factors on the construction site.

The investment in research and development of the U.S. construction industry is less than 0.5% of sales volume. In Japan, the largest construction companies such as Shumizu, Taisei, Kajima, Obayashi, and Takenaka invest about 1% of annual gross revenue in research and development [Cousineau and Miura, 1998]. Questions have arisen regarding the construction industry’s ability to meet the demands for construction in the 21st century. To remain competitive in today’s construction marketplace, the U.S. construction industry must introduce advanced technologies, in particular, construction automation and robotics technologies, in order to solve the problems mentioned above.

Construction has traditionally been resistant to technical innovation. Past efforts to industrialize construction in the U.S. were undertaken at the time when industrial automation technology was at its infancy. Additionally, engineering and economic analyses of prefabrication processes and systems were lacking. On the other hand, numerous construction tasks have or will become more attracted to automated technologies based upon the following characteristics: (1) repetitive, (2) tedious and boring, (3) hazardous to health, (4) physically dangerous, (5) unpleasant and dirty, (6) labor intensive, (7) vanishing skill area, (8) high skill requirement, (9) precision dexterity requirement, and (10) critical to productivity [Kangari and Halpin, 1989]. For example, some construction tasks have been historically noted for their arduous, repetitive nature, with relatively little dynamic decision making required on the part of a human laborer. Such tasks may include placing of concrete, placing of drywall screws, finishing of concrete, and placing of masonry block, among others. The work involved in these tasks is rather unattractive for humans. Robots, however, are applicable to these types of work tasks provided that the technology and economics are feasible.

There have been increasing demands to enhance intelligence of construction equipment and systems. Many researchers have investigated the addition of sensors and control systems to existing construction equipment. A limited amount of research, however, has been conducted in developing intelligent construction equipment and systems. For semiautonomous and autonomous equipment with great potential for impact on the construction industry, artificial intelligence (AI) is required to generate instructions and plans necessary to perform tasks in dynamically changing environments on their own.

Construction automation refers to the use of a mechanical, electrical, and computer-based system to operate and control construction equipment and devices. There are two types of construction automation:

1. Fixed construction automation
2. Programmable construction automation

Fixed construction automation involves a sequence of operations performed by equipment fixed in their locations. In other words, an automated facility, whether it is permanently indoors or temporarily on the construction site, is set up specifically to perform only one function or produce one product. In programmable construction automation, equipment has the ability to change its sequence of operations easily to accommodate a wide variety of products.

## 6.2 Fixed Construction Automation

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Fixed construction automation is useful in mass production or prefabrication of building components such as:

1. Reinforcing steel
2. Structural steel
3. Exterior building components (e.g., masonry, granite stone, precast concrete)

## Examples of Fixed Construction Automation

In this section, selected examples of fixed construction automation are highlighted.

### Automated Rebar Prefabrication System

The automated rebar prefabrication system places reinforcing bars for concrete slab construction. The system consists of a NEC PC98000XL high-resolution-mode personal computer that uses AutoCAD™, DBASE III Plus™, and BASIC™ software. The information regarding number, spacing, grade and dimension, and bending shapes of rebars is found from the database generated from an AutoCAD file. This information is used by an automatic assembly system to fabricate the rebar units.

The assembly system consists of two vehicles and a steel rebar arrangement support base. Of the two vehicles, one moves in the longitudinal direction and the other in the transverse direction. The longitudinally moving vehicle carries the rebars forward until it reaches the preset position. Then, it moves backward and places the rebars one by one at preset intervals on the support base. Upon completion of placement of the rebars by the longitudinally moving vehicle, the transversely moving vehicle places the rebars in a similar manner. The mesh unit formed by such a placement of rebars is tied together automatically [Miyatake and Kangari, 1993].

### Automated Brick Masonry

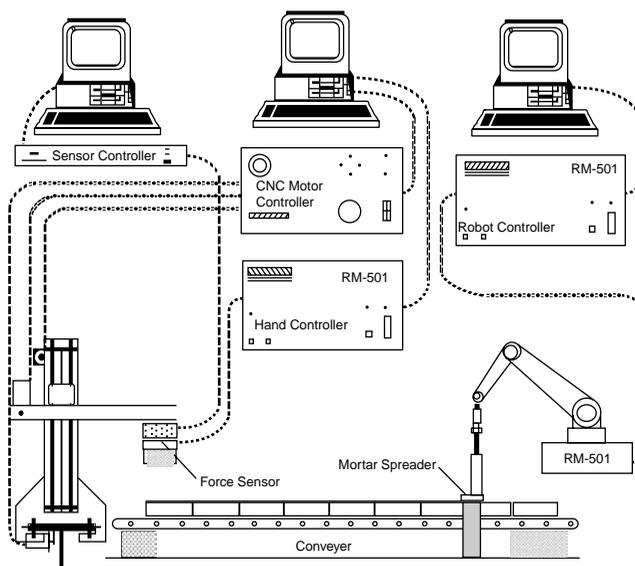
The automated brick masonry system, shown in Fig. 6.1, is designed to spread mortar and place bricks for masonry wall construction. The system consists of:

1. Mortar-spreading module
2. Brick-laying station

The controls of the system are centered around three personal computers responsible for:

1. Collecting and storing data in real time
2. Interfacing a stepping-motor controller and a robot controller
3. Controlling the mortar-spreading robot

A Lord 15/50 force-torque sensor is used to determine the placing force of each brick. The system is provided with an integrated control structure that includes a conveyor for handling the masonry bricks [Bernold et al., 1992].



**FIGURE 6.1** Automated brick masonry. (Source: Bernold et al. 1992. Computer-Controlled Brick Masonry. *Journal of Computing in Civil Engineering*, ASCE. 6(2):147–161. Reproduced by permission of ASCE.)

## Fully Automated Masonry Plant

The fully automated masonry plant is designed to produce different brick types with the production capacity of 300 m<sup>2</sup> wall elements per shift. The system consists of several components: a master computer, a database server, a file server, stone cutters, masonry robots, pallet rotation systems, refinement systems, storage systems, transversal platforms, a disposition management system, an inventory management system, and a CAD system.

Two individual brick types can be managed in parallel by unloading the gripper and the cutter-system consisting of two stone saws. By conveyer systems, stone units and fitting stones are transported to the masonry robot system. The masonry robots move two bricks at each cycle to the growing wall after a mortar robot puts a layer of mortar on it. A pallet rotation system carries the wall to the drying chamber. After 48 hours, the wall is transported to destacking stations to group the wall elements of the same order. Finally, grouped wall elements are transported to the construction site [Hanser, 1999].

## Automated Stone Cutting

The purpose of the automated stone-cutting facility is to precut stone elements for exterior wall facings. The facility consists of the following subsystems:

1. Raw materials storage
2. Loading
3. Primary workstation
4. Detail workstation
5. Inspection station
6. End-product inventory

A special lifting device has been provided for automated materials handling. The boom's rigidity enables the computation of exact location and orientation of the hook. Designs for the pallets, the primary saw table, the vacuum lift assembly, and the detail workstation have also been proposed [Bernold et al., 1992].

## 6.3 Programmable Construction Automation

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Programmable construction automation includes the application of the construction robots and numerical control machines described below.

### Construction Robots

The International Standards Organization (ISO) defines a robot as “an automatically controlled, re-programmable, multi-purpose, manipulative machine with several reprogrammable axes, which may be either fixed in place or mobile for use in industrial automation applications” [Rehg, 1992]. For construction applications, robots have been categorized into three types [Hendrickson and Au, 1988]:

1. Tele-operated robots in hazardous or inaccessible environments
2. Programmed robots as commonly seen in industrial applications
3. Cognitive or intelligent robots that can sense, model the world, plan, and act to achieve working goals

The important attributes of robots from a construction point of view are their (1) manipulators, (2) end effectors, (3) electronic controls, (4) sensors, and (5) motion systems [Warszawski, 1990]. For further explanation of these attributes, refer to the definitions section at the end of this chapter.

### Applications of Construction Robots

Table 6.1 presents a partial list of construction robot prototypes developed in the U.S. and in other countries. Brief summaries of several of these prototypes are provided below. Several of these descriptions have been adapted from Skibniewski and Russell [1989].

### ***John Deere 690C Excavator***

The John Deere 690C excavator is a tele-operated machine; that is, it is fully controlled by a human operating from a remote site. It is equipped with a model 60466T, six-cylinder, four-stroke turbocharged diesel engine, producing a maximum net torque of 450 ft-lb (62.2 kgf-m) at 1300 revolutions per minute (rpm) [*Technical Specifications*, 1985]. The engine propels the excavator at traveling speeds ranging from 0 to 9.8 mph (15.8 km/h).

The arm on the 690C excavator has a lifting capacity of 11,560 lb (5243 kgf) over side and 10,700 lb (4853 kgf) over end. The rated arm force is 15,900 lb (7211 kgf), and the bucket digging force is 25,230 lb (11,442 kgf) [*Technical Specifications*, 1985].

The John Deere 690C excavator has been implemented in a cooperative development program with the U.S. Air Force within the Rapid Runway Repair (RRR) project. The major task of the RRR is the repair of runways damaged during bombing raids. The Air Force is currently investigating other areas in which the 690C could be implemented, including heavy construction work, combat earthmoving in forward areas, mine-field clearing, and hazardous-material handling.

### ***Robot Excavator (REX)***

The primary task of the robot excavator (REX) is to remove pipelines in areas where explosive gases may be present. This robot is an autonomous machine able to sense and adjust to its environment. REX achieves its autonomous functions by incorporating three elements into its programming [Whittaker, 1985a]:

1. Subsurface premapping of pipes, structures, and other objects is possible using available utility records and ground-penetrating sensors. Magnetic sensing is the leading candidate for premapping metallic pipes.
2. Primary excavation for gross access near target pipes is possible. Trenching and augering are the leading candidates for this operation.
3. Secondary excavation, the fine and benign digging that progresses from the primary excavation to clear piping, can be accomplished with the use of a supersonic air jet.

The hardware that REX uses for primary excavation is a conventional backhoe retrofitted with servo valves and joint resolvers that allow the computer to calculate arm positions within a three-dimensional space. The manipulator arm can lift a 300 lb (136 kg) payload at full extension and over 1000 lb (454 kg) in its optimal lifting position.

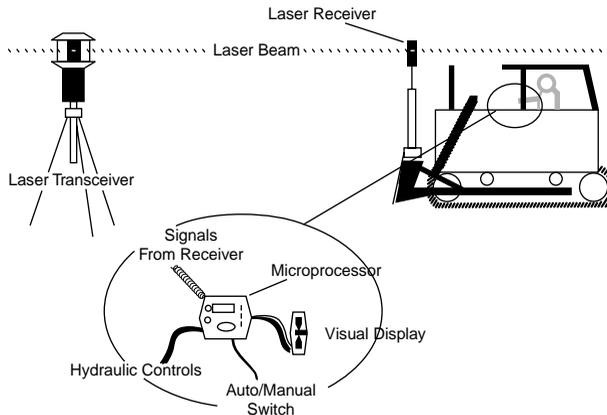
REX uses two primary sensor modes: tactile and acoustic. The tactile sensor is an instrumented compliant nozzle. The instrumentation on the nozzle is an embedded tape switch that is activated when the nozzle is bent. The second sensor employed in excavation is an acoustical sensor, allowing for three-dimensional imaging.

### ***Haz-Trak***

Haz-Trak, developed by Kraft Telerobotics, is a remotely controlled excavator that can be fitted with a bulldozer blade for grading, backfilling, and leveling operations [Jaselskis and Anderson, 1994]. Haz-Trak uses force feedback technology, allowing the operator to actually feel objects held by the robot's manipulator. The operator controls the robot's arm, wrist, and grip movements through devices attached to his or her own arm. Thus, the robot arm instantly follows the operator's movements.

### ***Pile-Driving Robot***

The Hitachi RX2000 is a pile-driving machine directed by a computer-assisted guiding system. It consists of a piling attachment (such as an earth auger or a vibratory hammer) directly connected to the tip of a multijointed pile driver arm. The pile driver arm uses a computer-assisted guiding system called an "arm tip locus control." Coordinates of arm positions are calculated using feedback from angle sensors positioned at joints along the arm. A control lever operation system is provided to increase efficiency. The compactness of the RX2000 and its leaderless front attachment enable efficient piling work even in congested locations with little ground stabilization. Further, the vibratory hammer has a center hole



**FIGURE 6.2** Laser-aided grading system. (Source: Tatum, C. B., and Funke, A. T. 1988. Partially Automated Grading: Construction Process Innovation. *Journal of Construction Engineering and Management*, ASCE. 114(1):19–35. Reproduced by permission of ASCE.)

chunk that firmly chucks the middle part of a sheet pile or an H-steel pile. Hence, pile length is not limited by the base machine’s dump height [Uchino et al., 1993].

### **Laser-Aided Grading System**

Spectra-Physics of Dayton, OH, developed a microcomputer-controlled, laser-guided soil-grading machine (see Fig. 6.2). A laser transmitter creates a plane of light over the job site. Laser light receptors mounted on the equipment measure the height of the blade relative to the laser plane. Data from the receiver are then sent to the microcomputer that controls the height of the blade through electronically activated valves installed in the machine’s hydraulic system. A similar device has been developed by Agtek Company in cooperation with a construction contractor in California [Paulson, 1985]. An automated soil-grading process implemented by these machines relieves the operator from having to manually position and control the grading blades, thus increasing the speed and quality of grading, as well as work productivity [Tatum and Funke, 1988].

### **Automatic Slipform Machines**

Miller Formless Systems Company developed four automatic slipform machines — M1000, M7500, M8100, and M9000 — for sidewalk and curb and gutter construction [*Technical Specifications*, 1988]. All machines are able to pour concrete closer to obstacles than is possible with alternative forming techniques. They can be custom-assembled for the construction of bridge parapet walls, monolithic sidewalk, curb and gutter, barrier walls, and other continuously formed elements commonly used in road construction.

The M1000 machine is suitable for midrange jobs, such as the forming of standard curb and gutter, sidewalks to 4 ft, and cul-de-sacs. The M7500 is a sidemount-design machine for pouring barrier walls, paved ditches, bridge parapets, bifurcated walls, and other types of light forming jobs. The M8100 is a midsize system with a sidemount design combined with straddle-paving capabilities. The machine can be extended to 16-ft (4.88-m) slab widths with added bolt-on expansion sections. The M9000 multidirectional paver is designed for larger-volume construction projects. It can perform an 18-ft (5.49-m) wide paving in a straddle position. Options are available for wider pours, plus a variety of jobs from curbs to irrigation ditches, in its sidemount mode.

### **Horizontal Concrete Distributor**

The HCD, developed by Takenaka Company, is a hydraulically driven, three-boom telescopic arm that cantilevers from a steel column. The boom can extend 66 ft (20 m) in all directions over an 11,000-ft<sup>2</sup> (1000-m<sup>2</sup>) surface area. A cockpit located at the end of the distributor houses the controls for an operator

to manipulate the boom direction and flow of concrete. The weight of the robot is 4.97 tons (4508 kgf), and it can be raised along the column by jacks for the next concrete pour. On average, the relocation procedure takes only 1.5 h [Sherman, 1988].

### ***Shotcrete Robot***

Traditionally, in tunneling work, a skilled operator has been needed to regulate the amount of concrete to be sprayed on a tunnel surface and the quality of the hardening agent to be added, both of which depend on the consistency of the concrete. Kajima Construction Company of Japan developed and implemented a semiautonomous robotic applicator by which high-quality shotcrete placement can be achieved [Sagawa and Nakahara, 1985].

### ***Slab-Finishing Robot***

The robot designed for finishing cast-in-place concrete slabs by Kajima Construction Company, shown in Fig. 6.3, is mounted on a computer-controlled mobile platform and equipped with mechanical trowels that produce a smooth, flat surface [Saito, 1985]. By means of a gyrocompass and a linear distance sensor, the machine navigates itself and automatically corrects any deviation from its prescheduled path. This mobile floor-finishing robot is able to work to within 1 m of walls. It is designed to perform the work of at least six skilled workers.

### ***Auto-Claw and Auto-Clamp***

Two robotic devices used for steel beam and column erection on construction sites have been developed by Obayashi Construction Company of Japan. Both construction robots have been developed to speed up erection time and to minimize the risks incurred by steelworkers. Both have been implemented on real job sites.

The auto-claw consists of two steel clamps extended from a steel-encased unit containing a DC battery pack, electrical panel, and microprocessor unit, which is in turn suspended from a standard crane. The two clamps have a rated capacity of two tons (1,824 kgf) each and can be adjusted to fit beam flanges from 8 to 12 in. (203.2 to 304.8 mm). The clamps are automatically released by remote radio control once the beam is securely in place. Fail-safe electronic circuitry prevents the accidental release of the clamps during erection by keeping the circuit broken at such times. The steel beams require no special preparation for using this robot.

The auto-clamp's essential purpose and mechanics are the same as for the auto-claw, except that the auto-clamp uses a special electrosteel cylinder tube to secure and erect columns. A steel appendage plate with a hole in the center must be welded to one end of the column. The steel cylinder is electrically inserted and locked into the hole by remote control, whereupon the column can be erected. The auto-clamp has a rated lifting capacity of 15 tons (13,605 kg). The appendage plates must be removed after the columns are erected. Like the auto-claw, the auto-clamp is equipped with a fail-safe system preventing the cylinder from retracting from the hole during erection [Sherman, 1988].

### ***Automated Pipe Construction***

Research into automated pipe construction is under way at the University of Texas at Austin [O'Connor et al., 1987]. Research efforts are focused on developing and integrating three pipe production technologies: bending, manipulation, and welding. The pipe manipulator, shown in Fig. 6.4, was adapted from a 20-ton rough-terrain hydraulic crane with an attachment to the main boom [Hughes et al., 1989]. The attachment includes an elevating, telescoping, auxiliary boom with a wrist and pipe-gripping jaws. Associated research has concentrated on improving productivity through automated lifting and manipulating of horizontal piping [Fisher and O'Connor, 1991].

### ***Blockbots***

Another application involves the design, development, and testing of the “blockbot” robot intended to automate the placement of masonry blocks to form walls. The complete wall assembly consists of four major components [Slocum et al., 1987]:

1. A six-axis “head” that will actually place the blocks on the wall
2. A 20- to 30-ft (6- to 9.1-m) hydraulic scissors lift used to roughly position the placement head vertically and longitudinally
3. A large-scale metrology system, sensors, and other related computer control equipment
4. A block-feeding system/conveyor to continually supply the placement head

To facilitate construction, the blocks are stacked upon each other with no mortar between the levels. The wall is then surface-bonded using Surewall™, a commercial fiberglass-reinforced bonding cement. This process produces a wall with strength comparable to that of a traditional mortar wall.

### ***Wallbots***

Researchers at the Massachusetts Institute of Technology (MIT) are engaged in the Integrated Construction Automation Design Methodology (ICADM) project [Slocum et al., 1987]. This work attempts to integrate the efforts of material suppliers, architects, contractors, and automated construction equipment designers.

The process of building interior wall partitions is divided between two separate robots: a trackbot and a studbot. Circumventing the need for complex navigational systems, the trackbot is guided by a laser beacon aligned manually by a construction worker. The trackbot is separated into two parallel workstations: an upper station for the ceiling track and a lower station for the floor track. Detectors are mounted on the ends of the effector arms to ensure that the laser guidance system achieves the necessary precision. The placement of the track consists of four steps: (1) the effector arm grabs a piece of track, (2) the effector arm positions the track, (3) two pneumatic nail guns fasten the track, and (4) the trackbot moves forward, stopping twice to add additional fasteners.

Once the trackbot has completed a run of track, the studbot can begin placing studs. Location assessment is made by following the track and employing an encoding wheel or an electronic distance measuring (EDM) instrument. The studbot then references a previously sorted floor plan to ascertain locations of studs to be placed. The stud is removed from its bin and placed into position. The positioning arm then spot-welds the stud into place.

### ***Interior Finishing Robot***

An interior finishing robot, shown in Fig. 6.5, can execute the following tasks: (1) building walls and partitions, (2) plastering walls and ceilings, (3) painting walls and ceilings, and (4) tiling walls. The arm of the robot has six degrees of freedom with a nominal reach of 5.3 ft (1.6 m) and a lifting capacity of 66 lb (145 kgf). The robot is designed to perform interior finishing work in residential and commercial buildings with single or multiple floor levels and interior heights of 8.5 to 8.8 ft (2.60 to 2.70 m). A three-wheel mobile carriage measuring 2.8 ¥ 2.8 ft (0.85 ¥ 0.85 m) enables motion of the robot between static workstations [Warszawski and Navon, 1991; Warszawski and Rosenfeld, 1993].

### ***Fireproofing Spray Robot***

Shimizu Company has developed two robot systems for spraying fireproofing material on structural steel [Yoshida and Ueno, 1985]. The first version, the SSR-1, was built to (1) use the same materials as in conventional fireproofing, (2) work sequentially and continuously with human help, (3) travel and position itself, and (4) have sufficient safety functions for the protection of human workers and of building components. The second robot version, the SSR-2, was developed to improve some of the job site functions of SSR-1. The SSR-2 can spray faster than a human worker but requires time for transportation and setup. The SSR-2 takes about 22 min for one work unit, whereas a human worker takes about 51 min. The SSR-2 requires relatively little manpower for the spraying preparation — only some 2.1 person-days compared with 11.5 for the SSR-1. As the positional precision of the robot and supply of the rock wool feeder were improved, the SSR-2 could achieve the same quality of dispersion of spray thickness as for that applied by a human worker.

### ***Exterior Wall Painting Robot***

The exterior wall painting robot, shown in Fig. 6.6, paints walls of high-rise buildings, including walls with indentations and protrusions. The robot is mounted on mobile equipment that permits translational motion along the exterior wall of a building. The robot consists of the following:

1. Main body that sprays paint
2. Moving equipment to carry the robot main body to the proper work position
3. Paint supply equipment
4. A controller

The robot main body consists of the following:

1. Main frame
2. Painting gun
3. Gun driver
4. Control unit

The painting gun is driven in three principal translational directions ( $x$ ,  $y$ , and  $z$ ). The painting gun is also provided with two rotational degrees of freedom. The robot moving equipment consists of the following:

1. A transporter that propels the moving equipment along the outside of the building being painted
2. A work stage on which the robot main body is mounted
3. A mast that serves as a guide for raising and lowering the work stage

The top of the mast is attached to a travel fitting, and the fitting moves along a guide rail mounted on the top of the building [Terauchi et al., 1993].

### ***Integrated Surface Patcher (ISP)***

Secmar Company of France developed a prototype of the integrated surface patcher (ISP) [Point, 1988]. The unit consists of the following components:

1. A 19-ton (17,234-kgf) carrier with rear-wheel steering
2. A 3.9-yd<sup>3</sup> (3-m<sup>3</sup>) emulsion tank
3. A 5.2-yd<sup>3</sup> (4-m<sup>3</sup>) aggregate container
4. A built-in spreader working from the tipper tailboard (a pneumatic chip spreader with 10 flaps and a 10-nozzle pressurized bar)
5. A compaction unit

The ISP unit has a compressor to pressurize the emulsion tank and operate the chip-spreading flaps. The machine uses a hydraulic system driven by an additional motor to operate its functional modules. The electronic valve controls are operated with power supplied by the vehicle battery.

The ISP is used primarily for hot resurfacing repairs, including surface cutting, blowing and tack coating with emulsion, as well as for repairs requiring continuous treated or nontreated granular materials. The unit is suitable for deep repairs using aggregate-bitumen mix, cement-bound granular materials, and untreated well-graded aggregate, as well as for sealing wearing courses with granulates.

The current design of the ISP allows only carriageway surface sealing. It is thus not well suited for surface reshaping or pothole filling. It is used only for routine maintenance tasks. In operational terms, ISP is not capable of on-line decision making on how to proceed in the case of an irregular crack or other nonpredetermined task. However, automated patching can be started manually or automatically, depending on the presence of optical readers mounted on the equipment that read the delimiters of the work area, and on the mode of action chosen by the operator.

### ***Autonomous Pipe Mapping***

Another application is the development of an automated pipe-mapping system. Current manual methods are slow, inefficient, qualitative, and nonrepetitive. The intention of the system is to autonomously

**TABLE 6.1** Example Construction Robotic Prototypes

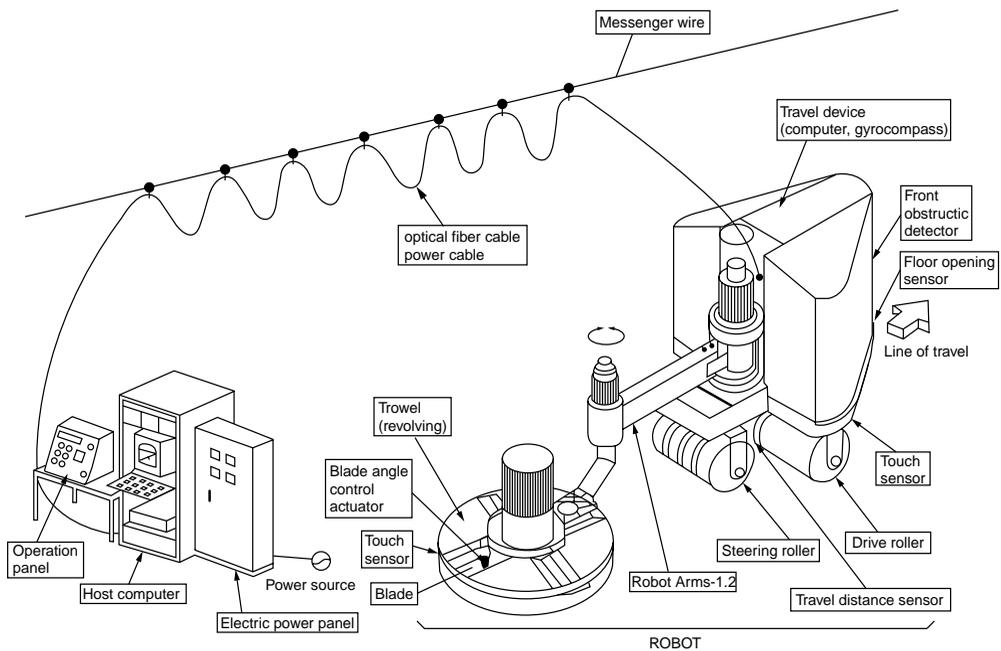
System Description	Application	Research Center
<b>Excavation</b>		
John Deere 690C Robot excavator (REX)	Tele-operated excavation machine Autonomous excavation, sandblasting, spray washing, and wall finishing	John Deere, Inc., Moline, IL The Robotics Institute, Carnegie- Mellon Univ., Pittsburgh, PA
Super hydrofraise excavation control system	Excavate earth	Obayashi Co., Japan
Haz-Trak Hitachi RX2000	Remotely controlled excavation Pile driving	Kraft Telerobotics Hitachi Construction Machinery Co., Japan
Remote core sampler (RCS)	Concrete core sampling for radiated settings	The Robotics Institute, Carnegie- Mellon Univ., Pittsburgh, PA
Laser-aided grading system	Automatic grading control for earthwork	Gradeway Const. Co. and Agtek Dev. Co., San Francisco, CA; Spectra- Physics, Dayton, OH
<b>Tunneling</b>		
Shield machine control system	Collect and analyze data for controlling tunneling machine	Obayashi Co. and Kajima Co., Japan
Microtunneling machine Tunnel wall lining robot	Tele-operated microtunneling Assemble wall liner segments in tunnels for sewer systems and power cables	American Augers, Wooster, OH Ishikawajima-Harima Heavy Industries, Japan; Electric Power Co., Japan; Kajima Co., Japan
<b>Concrete</b>		
Automatic concrete distribution system	Carry concrete from batching plant to the cable crane	Obayashi Co., Japan
Automatic slipform machines	Placement of concrete sidewalks, curbs, and gutters	Miller Formless Systems Co., McHenry, IL; Gomaco, Ida Grove, IA
Concrete placing robot for slurry walls	Place and withdraw tremie pipes and sense upper level of concrete as it is poured	Obayashi Co., Japan
Shotcrete robot	Spray concrete tunnel liner	Kajima Co., Japan; Obayashi Co., Japan
HMC handling robot	Transport and place HMC concrete forms	Taisei Co., Japan
Rebar bending robot	Bend rebar	Obayashi Co., Japan
Rebar preassembly robot	Place and tie rebar	Shimizu Co., Japan
Rebar fabricating robot	Fabricate beam rebar, place and tie rebar	Taisei Co., Japan
Automatic concrete vibrator tamper	Vibrate cast-in-place concrete	Obayashi Co., Japan
Automatic laser beam-guided floor robot	Finish surface of cast-in-place concrete	Obayashi Co., Japan
Slab-finishing robot	Finish surface of cast-in-place concrete	Kajima Co., Japan
Rebar placing robot	Place heavy rebar	Kajima Co., Japan
Rebar installation crane	Place heavy rebar	Takenaka Co., Japan
Horizontal concrete distributor (HCD)	Place concrete for horizontal slabs	Takenaka Komuten Co., Japan
Mobile concrete distributor	Concrete distribution	Tokyu Co., Japan
CONDIS	Concrete distribution	Takenaka Co., Japan
ACSUS	Concrete distribution	Konoike Construction, Japan
CALM	Concrete leveling	Fujita Co., Japan
Mobile screeding robot	Level fresh concrete	Shimizu Co., Japan; Yanmar Diesel, Japan
Screed Robo	Level fresh concrete	Takenaka Co., Japan
Kote-King	Finish large floor areas	Kajima Co., Japan
Surf-Robo	Finish large floor areas	Takenaka Komuten Co., Japan
Flat-kun	Finish large floor areas	Shimizu Co., Japan
Concrete floor finishing robot	Finish large floor areas	Hazama Co., Japan; Mitsubishi Co., Japan; Eroika Co., Japan
Water removing robot	Remove surface water	Takenaka Co., Japan

**TABLE 6.1** Example Construction Robotic Prototypes

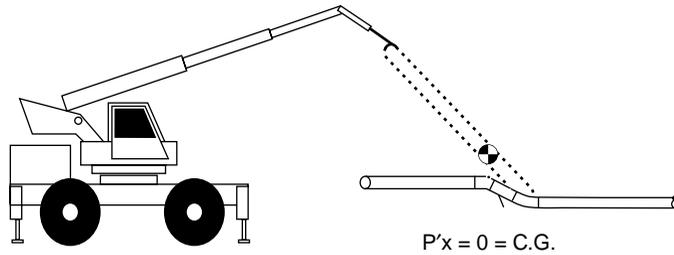
System Description	Application	Research Center
<b>Structural Members</b>		
Auto-claw, auto-clamp	Erect structural steel beams and columns	Obayashi Co., Japan
Mighty shackle ace	Handle structural steel	Shimizu Co., Japan
Structural element placement	Place reinforcing steel	Kajima Co., Japan
TAP system	Straighten structural steel	Taisei Co., Japan
Structural element welding	Weld large structural blocks for cranes and bridges	Mitsubishi Heavy Industries Co., Japan
Fujita welding robot	Weld structural steel columns	Fujita Co., Japan
Obayashi welding robot	Weld structural steel columns	Obayashi Co., Japan
Shimizu welding robot	Weld structural steel columns	Shimizu Co., Japan
Taisei welding robot	Weld structural steel columns	Taisei Co., Japan
Takenaka welding robot	Weld structural steel columns	Takenaka Co., Japan
Welding robot	Weld structural steel columns	Kajima Co., Japan; Mitsubishi Heavy Industry, Japan
Shear stud welder	Weld shear connectors in composite steel/concrete construction	Massachusetts Institute of Technology, Cambridge
Automatic carbon fiber wrapper	Wrap existing structures with carbon steel	Obayashi Co., Japan
SSR-1, SSR-2, and SSR-3	Spray fireproofing material on steel structure	Shimizu Co., Japan
Fireproof spray robot	Spray fireproofing material on steel structure	Fijita Co., Japan; Shimizu Co., Japan; Nichias Co., Japan
Automated pipe construction	Pipe bending, pipe manipulation, and pipe welding	University of Texas, Austin
Blockbots	Construction of concrete masonry walls	Massachusetts Institute of Technology, Cambridge
Wallbots	Construction of interior partitions, metal track studs	Massachusetts Institute of Technology, Cambridge
Interior finishing	Building walls and partitions, plastering, painting, and tiling walls and ceilings	Israel Institute of Technology, National Building Research Institute
<b>Non-concrete Spraying</b>		
Paint-spraying robot	Paint balcony rails in high-rise buildings	Shimizu Co., Fijita Co., Kajima Co., and Taisei Co., Japan
KFR-2	Spray paint	Kumagai Co., Japan
SB Multi Coater	Spray paint	
OSR-1	Spray paint	Shimizu Co., Japan
TPR-02	Spray paint	Taisei Co., Japan
<b>Inspection</b>		
Wall inspection robot (Kabedohda I and II)	Inspect reinforced concrete walls Inspect façade	Obayashi Co., Japan Kajima Co., Shimizu Construction Co., Takenaka Co., and Taisei Co., Japan
Bridge inspection robot	Inspect structural surface of a bridge	University of Wales
GEO robot	Finish façade/surface	Eureka, France
Kajima tile inspection robot	Detect bonding condition of both tile and mortar	Kajima Co., Japan
Kumagai tile inspection robot	Detect bonding condition of both tile and mortar	Kumagai Co., Japan
Takenaka	Detect bonding condition of both tile and mortar	Takenaka Co., Japan
TG-02	Detect bonding condition of both tile and mortar	Taisei Co., Japan
Pipe inspection robot	Measure pipe thickness	Mitsui Construction, Japan
Pipero	Measure pipe thickness	Obayashi Co., Japan

### Other

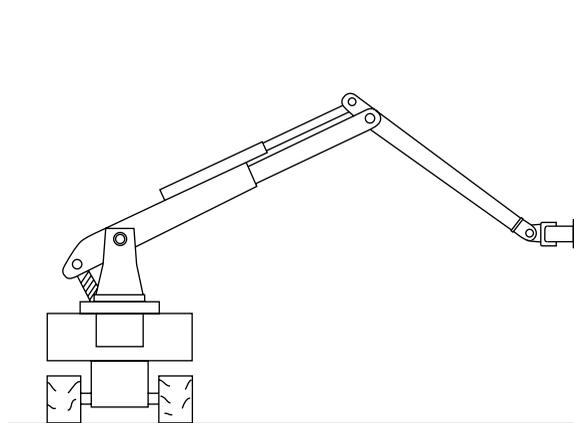
Clean room inspection and monitoring robot (CRIMRO)	Inspect and monitor the amount of particles in the air	Obayashi Co., Japan
K-Creitor	Inspect clean room	Kumagai Gumi, Japan
Leak robo	Inspect clean room	Hazama Gumi, Japan
Integrated surface patcher (ISP) material handling	Hot resurfacing on highways, pick and distribute construction materials (e.g., prefabricated concrete materials and pipe)	Secmar Co., France; Tokyo Construction Co., Japan; Hitachi Construction Co., Japan
Autonomous pipe mapping	Mapping subsurface pipes	The Robotics Institute, Carnegie-Mellon Univ., Pittsburgh, PA
Terregator	Autonomous navigation	The Robotics Institute, Carnegie-Mellon Univ., Pittsburgh, PA
Remote work vehicle (RWV)	Nuclear accident recovery work, wash contaminated surfaces, remove sediments, demolish radiation sources, apply surface treatment, package and transport materials	The Robotics Institute, Carnegie-Mellon Univ., Pittsburgh, PA
ODEX III	Inspection, surveillance, material transport	Odetics, Inc., French Commissariat a l'Energie Atomique, France
CFR1	Material transport (ceiling board)	Shimizu Co., Japan
Boardman-100	Material transport (plaster board)	Taisei Co., Japan
Mighty hand	Material transport	Kajima Co., Japan
Sky hand	Material transport	Komatsu Co., Japan
Balance hand	Material transport	Komatsu Co., Japan
Lady bug	Detect underground	Tokyo Construction, Japan



**FIGURE 6.3** Slab-finishing robot. (Source: Skibniewski, M. J. 1988. *Robotics in Civil Engineering*. Van Nostrand Reinhold, New York.)



**FIGURE 6.4** Pipe manipulator. (Source: Fisher, D. J., and O'Connor, J. T. 1991. Constructability for Piping Automation: Field Operations. *Journal of Construction Engineering and Management*, ASCE. 117(3):468–485. Reproduced by permission of ASCE.)



**FIGURE 6.5** Interior finishing robot. (Source: Warszawski, A. and Navon, R. 1991. Robot for Interior-Finishing Works. *Journal of Construction Engineering and Management*, ASCE. 117(3):402–422.)

establish size, depth, and orientation of buried pipes. This knowledge is extremely valuable in guiding excavation, validating as-built drawings, and building databases of piping details [Motazed and Whittaker, 1987].

The system is composed of a computer-controlled Cartesian  $x$ - $y$  table that allows various sensors to be swept across an arid area. The primary mapping is completed by a magnetic sensor that reads and records magnetic field intensities. These intensities are manipulated and interpreted, resulting in a line drawing representing the pipe locations. Higher-level processing estimates the depth of pipes and identifies interconnections such as elbows, tees, and crosses.

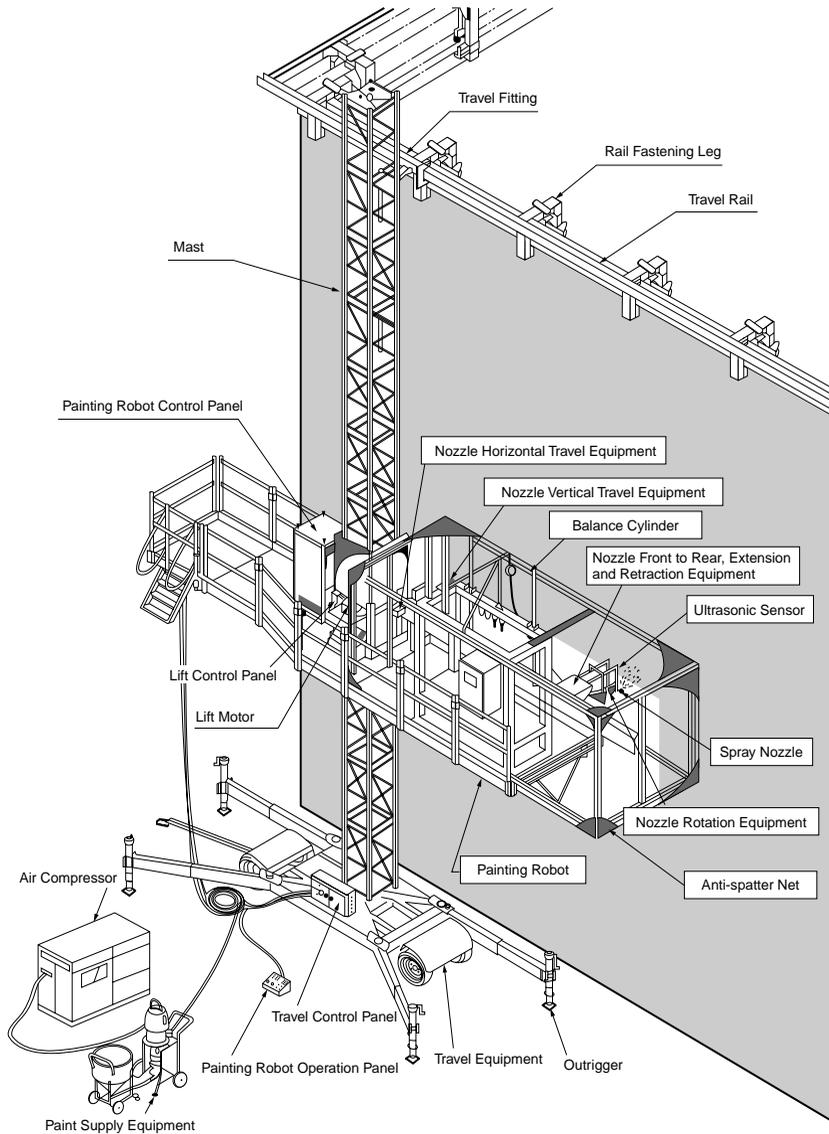
### **Terregator**

A machine that may be used to transport the autonomous pipe mapping system is the terregator. Designed for autonomous outdoor navigation, it can be directly applied on a construction site. The terregator has been specifically designed to be extremely durable and powerful in order to prevent problems that inhibit machines designed for interior use. Its gearing is adjustable to allow it to be configured as a low-speed, high-torque machine or as a high-speed, low-torque machine. The terregator has a six-wheel-drive design to ensure mobility on rough terrain.

The terregator is also designed as a fully enclosed modular system to facilitate repairs, additions, or system improvements. The subsystems include locomotion, power, backup power, computer and controls, serial links, sensors, and a video link [Whittaker, 1985b].

### **ODEX**

ODEX III, developed by Odetics, Inc., is a six-legged, tele-operated, high-strength robot designed for inspection, surveillance, and material handling in nuclear power plants and outdoor hazardous environments



**FIGURE 6.6** Exterior wall painting robot. (Source: Terauchi et al. 1993. Development of an Exterior Wall Painting Robot — Capable of Painting Walls with Indentations and Protrusions. *Proceedings, Tenth International Symposium on Automation and Robotics for Construction*. Houston, TX, pp. 363–370.)

[Jaselskis and Anderson, 1994]. ODEX III has telescoping legs that can extend it to a full height of 7.9 ft (2.4 m), a manipulator arm, and sensors on each foot to determine proper foot placement.

## Numerical Control

Numerical control refers to control of construction equipment using numbers [Luggen, 1984]. Questions such as “What numbers are used to control a piece of equipment?” and “In what format are they presented to the equipment?” are basic to understanding numerical control. Numerically controlled equipment consists of a machine control unit (MCU) and a machine tool (such as an end effector). The MCU cannot think, judge, or reason in relation to the environment in which it works. The machine accepts and responds to commands from the control unit [Luggen, 1984]. For example, a numerically controlled

pumped-concrete placement system may use numbers corresponding to (1) position ( $x, y, z$ ) of the discharging end of the placement pipe, (2) pumping pressure, and (3) the speed at which the discharging end of the placement pipe travels.

### Numerical Control (NC) Programs

The numerically controlled tool concept is based on textual programming methods to describe the structural components with the help of control surfaces. The description of the structural component is taken from the architectural drawing, converted to a code, and entered on a code carrier such as a computer disk. The format of the control data and the equipment commands need to be defined in detail. The control program consists of a sequence of commands in standardized symbolic format. The control program is transferred to the MCU, which translates the program to equipment-level instructions. The equipment-level instruction may be coded on perforated paper tape (NC tape), computer cards, magnetic tape, or floppy disks [Rembold et al., 1985].

Computers are used to derive equipment-level instructions using information from the control program. For a computer to accept and process the NC program data, the input programs must conform to the exacting requirements of the programming language of the computer. Hence, the general-purpose computer must be primed to handle the specific input program. The general-purpose computer is converted to a special-purpose computer through insertion of the NC program [Maynard, 1971].

The NC program, when processed by a computer, passes through three modules, as shown in Fig. 6.7. The input translator converts the NC program into a binary-coded system called machine language. Next, the machine language instructions are passed to the arithmetic section, which performs the required mathematical and geometric computations to calculate the path of the numerically controlled equipment. The post-processor checks the limitations of a particular piece of equipment (such as maximum pumping pressure or maximum velocity of the placing boom). The final output corresponds to the equipment-level instructions [Maynard, 1971].

### Computer Numerical Control (CNC)

A CNC system performs control functions similar to those of the NC system. However, CNC systems can have a microcomputer or multiprocessor architecture that is highly flexible. Logic control, geometric data processing, and NC program executions are supervised by a central processing unit (CPU). Hence, CNC is a software control system that performs the following tasks using a microcomputer: (1) system management, (2) data input/output, (3) data correction, (4) control of the NC program, (5) processing of operator commands, and (6) output of the NC process variables to the display [Rembold et al., 1985].

## 6.4 Computer-Integrated Construction (CIC)

Computer-integrated construction (CIC) is defined as “a strategy for linking existing and emerging technologies and people in order to optimize marketing, sales, accounting, planning, management, engineering, design, procurement and contracting, construction, operation and maintenance, and support functions” [Miyatake and Kangari, 1993]. Computer-aided design/computer-aided construction (CAD/CAC) systems are a major subset of CIC that focus on design and construction issues [Kunigahalli

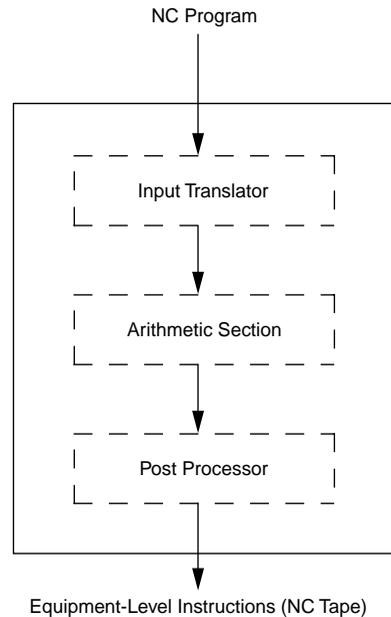


FIGURE 6.7 Software sections for NC programming processing.

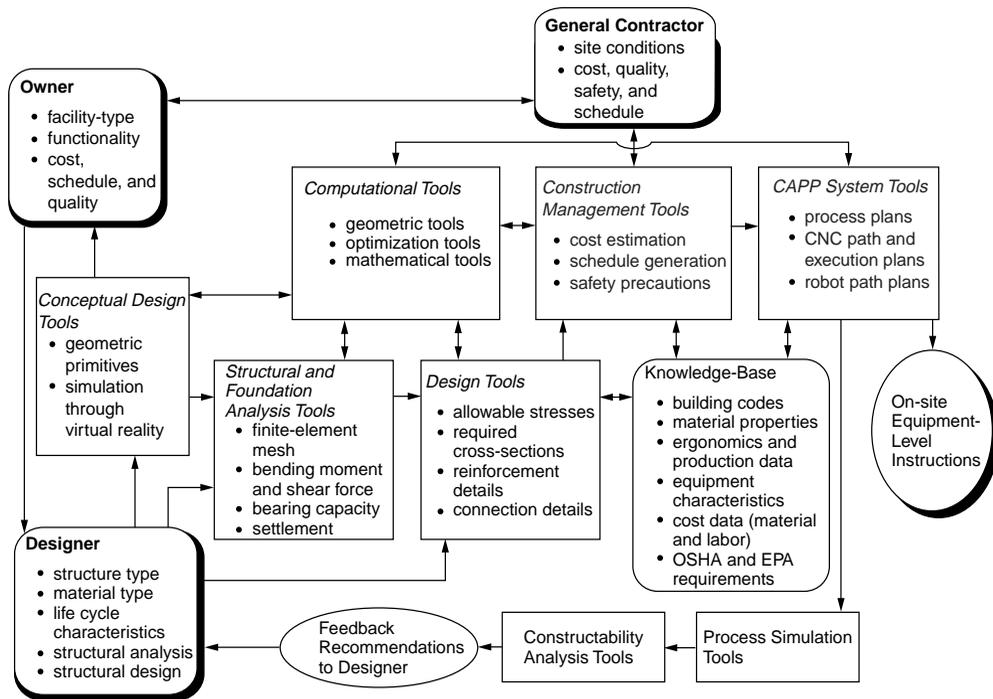


FIGURE 6.8 Framework of CAD/CAC systems.

and Russell, 1995]. Figure 6.8 presents the architecture of CAD/CAC systems. The development of CAD/CAC systems requires multidisciplinary research efforts in a variety of areas such as:

1. Computer-aided design (CAD) and geometric modeling
2. Algorithms and data structures
3. Artificial intelligence
4. Computer numerical control (CNC) and robotics
5. Group technology (GT)
6. Computer-aided process planning (CAPP)

Veeramani et al. [1998] draw attention to some of the significant research opportunities and challenges that exist in the areas of collaborative design and computer-integrated construction.

The implementation of CIC requires technologies related to (1) computer-aided engineering, (2) automatic material handling and data-identification systems, (3) network communications, (4) object-oriented programming, (5) knowledge-based systems (KBS), and (6) database management systems [Miyatake and Kangari, 1993]. Three of these areas are discussed below, followed by an example application of CIC.

## Computer-Aided Design (CAD) and Geometric Modeling

Computer-aided design (CAD) can be described as using a computer in the design process. A CAD model requires graphical data processing that comprises many techniques to process and generate data in the form of lines and figures. Thus, the input representation of textual or pictorial data is performed with techniques of character and pattern recognition [Rembold et al., 1985].

Models are used to represent physical abstract entities and phenomena, not just for the purpose of making pictures (creating sectional views), but to represent their structure and behavior [Foley and Van Dam, 1982]. CAD software modeling can be classified into the following three categories: (1) basic two-dimensional and three-dimensional wire-frame modeling, (2) surface modeling, and (3) solid modeling.

## **Basic Two-Dimensional and Three-Dimensional Wire-Frame Modeling**

In two-dimensional and three-dimensional wire-frame models, lines are stored as edges in an edge table, with each line pointing to its two end vertices stored in a vertex table. Wire-frame CAD models are not capable of recognizing the faces delineated by lines and vertices of the object being represented. Wire-frame CAD models are generally used as a substitute for manual drafting.

### ***Surface Modeling***

Surface modeling allows users to add faces to geometric models. Hence, hidden surface removal is possible in surface models. However, surface models do not contain information on the interior and exterior of the object.

### ***Solid Modeling***

A solid geometric model is an unambiguous and informationally complete mathematical representation of the physical shape of an object in a form that a computer can easily process [Mortenson, 1985]. Topology and algebraic geometry provide the mathematical foundation for solid modeling. Solid modeling's computational aspects include data structures and algorithms from computer science and application considerations from design and construction of engineering projects.

The following techniques are available for solid modeling of civil engineering facilities [Requicha, 1980]:

1. Primitive instancing
2. Cell decompositions
3. Spatial occupancy enumeration (SOE)
4. Constructive solid geometry (CSG)
5. Sweep representations
6. Boundary representation (B-Rep)

### ***Primitive Instancing***

The primitive instancing modeling technique consists of an independent approach to solid-object representation in the context of the group technology (GT) paradigm. The modeling approach is based on the notion of families of objects, with each member of the family being distinguishable by a few parameters. For example, columns, beams, and slabs can be grouped as separate families in the case of general buildings. Each object family is called a generic primitive, and individual objects within a family are referred to as primitive instances [Requicha, 1980].

### ***Cell Decompositions***

Cell decompositions are generalizations of triangulations. Using the cell decomposition modeling technique, a solid may be represented by decomposing it into cells and representing each cell in the decomposition. This modeling technique can be used for analysis of trusses and frames in industrial and general buildings, bridges, and other civil engineering facilities. In fact, the cell decomposition technique is the basis for finite-element modeling [Mortenson, 1985].

### ***Spatial Occupancy Enumeration (SOE)***

The spatial occupancy enumeration (SOE) technique is a special case of the cell decomposition technique. A solid in the SOE scheme is represented using a list of spatial cells occupied by the solid. The spatial cells, called *voxels*, are cubes of a fixed size lying in a fixed spatial grid. Each cell may be represented by the coordinates of its centroid. Cell size determines the maximum resolution. This modeling technique requires large memory space, leading to inefficient space complexity. However, this technique may be used for motion planning of automated construction equipment under complete-information models [Requicha, 1980].

### ***Constructive Solid Geometry (CSG)***

Constructive solid geometry (CSG), often referred to as building-block geometry, is a modeling technique that defines a complex solid as a composition of simpler primitives. Boolean operators are used to execute the composition. CSG concepts include regularized Boolean operators, primitives, boundary evaluation

procedures, and point membership classification. CSG representations are ordered binary trees. Operators specify either rigid motion, regularized union, intersection, or difference and are represented by nonterminal nodes. Terminal nodes are either primitive leaves that represent subsets of three-dimensional Euclidean space or transformation leaves that contain the defining arguments of rigid motions. Each subtree that is not a transformation leaf represents a set resulting from the application of the motional and combinational operators to the sets represented by the primitive leaves.

The CSG modeling technique can be adopted to develop computer-aided design and drafting (CADD) systems for civil engineering structures. It can be combined with primitive instancing that incorporates the group technology paradigm to assist the designer. Although CSG technique is most suitable for design engineering applications, it is not suitable for construction engineering applications, as it does not store topological relationships required for construction process planning [Requicha, 1980].

### ***Sweep Representation***

The sweep representation technique is based on the idea of moving a point, curve, or surface along a given path; the locus of points generated by this process results in one-dimensional, two-dimensional, and three-dimensional objects, respectively. Two basic ingredients are required for sweep representation: an object to be moved and a trajectory to move it along. The object can be a curve, surface, or solid. The trajectory is always an analytically definable path. There are two major types of trajectories: translational and rotational [Mortenson, 1985].

### ***Boundary Representation (B-Rep)***

The boundary representation modeling technique involves representing a solid's boundary by decomposing it into a set of faces. Each face is then represented by its bounding edges and the surface in which it lies. Edges are often defined in the two-dimensional parametric space of the surface as segments of piecewise polynomial curves. A simple enumeration of a solid's faces is sufficient to unambiguously separate the solid from its complement. However, most boundary representation schemes store additional information to aid feature extraction and determine topological relationships. The additional information enables intelligent evaluation of CAD models for construction process planning and automated equipment path planning required in CAD/CAC systems [Requicha and Rossignac, 1992; Kunigahalli et al., 1995; Kunigahalli and Russell, 1995].

The boundary representation technique, storing topological relationships among geometric entities, is most suitable for computer-aided generation of construction process plans. However, primitive instancing, sweep representation, and CSG techniques are useful in developing user friendly CAD software systems for the design of civil engineering structures. Hence, CAD systems that incorporate CSG or primitive instancing techniques during interactive design processes and that employ boundary representation techniques for internal storage of design information are efficient for use in CAD/CAC systems [Kunigahalli and Russell, 1995].

## **CAD Applications in Civil Engineering**

### ***AutoCAD***

AutoCAD is the most widely used CAD software in civil engineering applications. In an effort toward computer-integrated construction (CIC), researchers have developed a link between AutoCAD and a knowledge-based planning program [Cherneck et al., 1991].

### ***CATIA***

CATIA is a three-dimensional solid modeling software marketed by IBM Corporation. Stone & Webster Engineering Corporation, in cooperation with IBM, developed an integrated database for engineering, design, construction, and facilities management. The system uses the DB2 relational database management system and the CATIA computer-aided-design software system [Reinschmidt et al., 1991].

### ***Walkthrough™***

Bechtel Corporation developed a three-dimensional simulation system called Walkthrough to aid in marketing, planning, and scheduling of construction projects. Walkthrough was developed to replace the

use of plastic models as a design tool [Cleveland and Francisco, 1988]. It was designed to allow users to interact with a three-dimensional computer model as they would with a plastic model. The system uses three-dimensional, real-time animation that lets the user visually move through the computer model and observe visual objects. Graphics of the system are presented such that objects are recognizable to users not accustomed to typical CAD images. This includes the use of multiple colors and shading. Walkthrough uses a Silicon Graphics IRIS workstation with specialized processors facilitating the high-speed graphics required for real-time animation. This visualization and simulation system supports files from IGDS (Intergraph CAD system) and 3DM [Morad et al., 1992].

### ***Object-Oriented CAD Model***

An object-oriented CAD model for the design of concrete structures that uses EUROCODE2, a European standard for concrete structures, has been developed by German researchers. The primitive instancing solid-modeling technique was employed in the development of this object-oriented model [Reymendt and Worner, 1993]. A committee, entitled “NEW TECCMAR,” formed under the Japanese construction ministry, developed a three-dimensional finite-element method (FEM) program with an extended graphical interface to analyze general buildings [Horning and Kinura, 1993].

## **Automated Material Management**

Automated material management systems are another important function of CIC. They comprise automated material identification systems and automated material handling systems.

### **Automated Material Identification Systems**

When construction materials arrive at CIC job sites, they are identified at the unloading area, and the job site inventory database in the central computer is updated. CIC requires tight control on inventory and integrated operation of automated equipment. Further, all construction materials must be tracked from the time of their arrival at the job site to their final position in the finished facility. Such tracking of construction materials may be done by employing automated identification systems.

There are two means of tracking construction materials: direct and indirect. Direct tracking involves identifying a construction material by a unique code on its surface. This method of tracking can be employed with the use of large prefabricated components. Indirect tracking involves identifying construction material by a unique code on the material handling equipment. This method of tracking can be employed for tracking bulk materials such as paints [Rembold et al., 1985]. Select automatic identification systems for construction materials are described below.

### ***Bar Coding***

The U.S. Department of Defense (DOD) was the first organization to implement bar coding technology. The Joint Steering Group for Logistics Applications of Automated Marking and Reading Symbols (LOGMARS) spearheaded the DOD’s effort in the implementation of bar coding technology. The symbology of bar codes conveys information through the placement of wide or narrow dark bars that create narrow or wide white bars. With the rise of the LOGMARS project, code 39 (also called “3 of 9” coding) has become a standard for bar coding. To date, most construction bar code applications have used the code 39 symbology [Teicholz and Orr, 1987; Bell and McCullough, 1988].

Laser beams and magnetic foil code readers are two basic technologies available for reading bar codes. Lasers offer the ability to read bar codes that move rapidly. Magnetic code readers are among the most reliable identification systems. It is possible to transmit the code without direct contact between the code reader and the write head on the code carrier. When the workpiece passes the read head, the code is identified by the code reader [Teicholz and Orr, 1987; Rembold et al., 1985].

### ***Voice Recognition***

Voice recognition provides computers the capability of recognizing spoken words, translating them into character strings, and sending these strings to the central processing unit (CPU) of a computer. The objective of voice recognition is to obtain an input pattern of voice waveforms and classify it as one of

a set of words, phrases, or sentences. This requires two steps: (1) analyze the voice signal to extract certain features and characteristics sequentially in time and (2) compare the sequence of features with the machine knowledge of a voice, and apply a decision rule to arrive at a transcription of the spoken command [Stukhart and Berry, 1992].

### ***Vision Systems***

A vision system takes a two-dimensional picture by either the vector or the matrix method. The picture is divided into individual grid elements called pixels. From the varying gray levels of these pixels, the binary information needed for determining the picture parameters is extracted. This information allows the system, in essence, to see and recognize objects.

The vector method is the only method that yields a high picture resolution with currently available cameras. The vector method involves taking picture vectors of the scanned object and storing them at constant time intervals. After the entire cycle is completed, a preprocessor evaluates the recomposed picture information and extracts the parameters of interest [Rembold et al., 1985].

### **Automated Material Handling Systems**

Automated material handling systems play an important role in CIC. Efficient handling of construction materials, such as prefabricated and precast components, is possible through an effective automated material handling system operating in conjunction with an automated material identification system.

#### ***Towlines***

A towline consists of a simple track with a powered chain that moves carts or other carriers from pickup points to assigned destinations. Towlines can be controlled by sophisticated computer electronic techniques. Towlines interface efficiently with other automated material handling systems. Automated material identification systems can be easily integrated with towline material handling systems. Optical scanners or photoelectric readers can be used at important locations and intersections along the track to read the bar-coded information attached to the cart and relay signals to the control system. The control system then routes the cart to its destination [Considine and Considine, 1986].

#### ***Underhang Cranes***

There are two types of motor-driven underhang cranes: (1) single-bridge overhead cranes that can operate on multiple runways and (2) double-bridge overhead cranes that can achieve higher hook lifts with greater load-carrying capacity. A motor-driven crane consists of a track used for crane runways and bridge girders, the end trucks, the control package, a drive assembly, drive wheels, a drive line shaft, a traveling pushbutton control, and runway and cross-bridge electrification.

#### ***Power and Free Conveyor Systems***

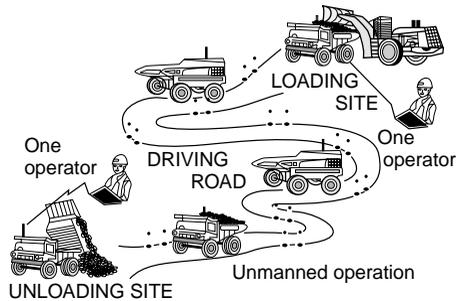
Conveyor systems allow precast or prefabricated components to be carried on a trolley or on multiple trolleys propelled by conveyors through some part of the system and by gravity or manual means through another part of the system. Conveyor systems provide the high weight capacities that are normally required in construction.

#### ***Inverted Power and Free Conveyor Systems***

An inverted power and free conveyor system is an upside-down configuration of the power and free conveyor system. The load is supported on a pedestal-type carrier for complete access.

#### ***Track and Drive Tube Conveyors***

Track and drive tube conveyors can be employed to transport components for prefabrication. This conveyor system consists of a spinning tube (drive tube) mounted between two rails. Carriers of prefabricated units need to be equipped with a drive wheel capable of moving between 0 and 45°. This drive wheel is positioned against the spinning drive tube. Speed of the moving component can be controlled by varying the angle of the drive wheel. When the drive wheel is in the 0° position, the carrier remains stationary. As the angle between the drive wheel and the drive tube is increased, the carrier accelerates forward.



**FIGURE 6.9** Autonomous dump truck system. (Source: Sugiyura et al. 1993. *Autonomous Dump Truck Systems for Transporting and Positioning Heavy-Duty Materials in Heavy Construction Sites. Proceedings, Tenth International Symposium on Automation and Robotics for Construction*. Houston, TX, pp. 253–260.)

### ***Automatic Vertical Transport System (AVTS)***

Fujita Corp.'s AVTS is a system under development that is designed to deliver material throughout the job site. The system uses an automated elevator system that automatically loads material onto a lift, hoists the material to the designated floor, and automatically unloads the lift [Webster, 1993].

### ***Interlocks***

Interlocks allow transfer of hoist carriers between adjacent crane runways, thereby maximizing the area covered by the overhead material handling systems. Interlocks also eliminate duplicate handling. Cross-connected, double-locking pins help to ensure that the safety stops will not operate until the crane and connecting track are in proper alignment.

### ***Automatically Guided Vehicles***

Automatically guided vehicles (AGVs) are the most flexible of all material handling equipment. AGVs can be controlled by programmable controllers, on-board microprocessors, or a central computer. Because of their lack of dependence on manual guidance and intervention, AGVs can also be categorized as construction robots. AGVs have their own motive power aboard. The steering system is controlled by signals emanating from a buried wire [Considine and Considine, 1986].

### ***Autonomous Dump Truck System***

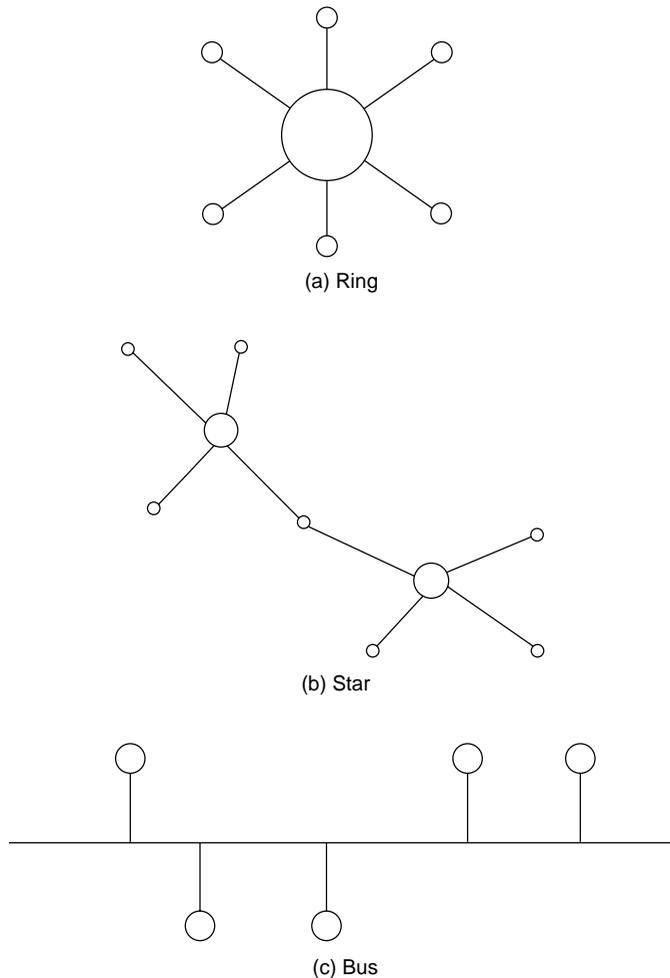
The autonomous dump truck system, shown in Fig. 6.9, enables driverless hauling operations, such as hauling of earth and gravel by dump trucks, on heavy construction sites. The two major functions of this system are autonomous driving function and advanced measurement function.

The driving distance and velocity of the vehicle are detected by encoder sensors attached to the truck tires. Direction of the vehicle is detected by a fiber-optic gyroscope. Positions of the vehicle are determined using data from the encoder sensors and fiber-optic gyroscope.

A laser transmitter/receiver is equipped at the left side of the test vehicle, and laser reflectors are installed along the driving route at a spacing of approximately 50 m. Positional errors accumulated in long-distance driving are corrected using the feedback information from the laser transmitter/receiver. The autonomous vehicle system recognizes the workers wearing helmets by utilizing a color image processor [Sugiyura et al., 1993].

## **Network Communication**

Communication technology, transferring information from one person or computer system to another, plays a vital role in the implementation of CIC. Establishment of an effective communications network such that originating messages receive the correct priority and accurate data arrive at the final destination is a difficult task [Miyatake and Kangari, 1993]. To ensure smooth operations in CIC, many automated devices and computers must be linked. Computer networking techniques enable a large number of computers to be connected. Computer networks can be classified as wide-area networks (WANs), which



**FIGURE 6.10** Three common network arrangements.

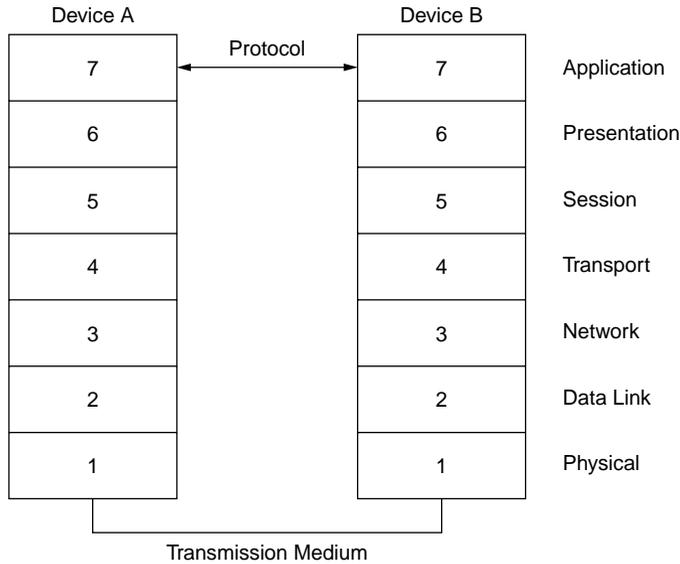
serve geometric areas larger than 10 km; local-area networks (LANs), which are confined to a 10-km distance; and high-speed local networks (HSLNs), which are confined to a distance less than 1 km.

Wide-area networks such as APPANET can be employed to connect the construction company's corporate office to various automated project sites. LANs combined with HSLNs can be employed to facilitate efficient data exchange among automated construction equipment (such as a CNC concrete placement machine, floor-leveling robots, and wall-painting robots) operating on job sites. Various gateways (computers that transfer a message from one network to another) can be used to link networks.

Three types of commonly used network arrangements — ring, star, and bus — are shown in Fig. 6.10. In a ring network arrangement, the connecting coaxial cable must be routed back to where it begins. This results in network breakdown whenever the ring breaks. The star network arrangement is easily expanded, but the network relies on a server at the center of the star. Further, all communications between nodes must pass through the center. The bus network arrangement is open-ended, and hence, a node can be added easily to the network [Chang et al., 1991].

The efficiency of a network system depends on the following parameters [Rembold et al., 1985]:

1. Transmission speed and maximum transmission distance
2. Time delay necessary to respond to interrupts and data requests
3. Additional hardware and software needed for expansion

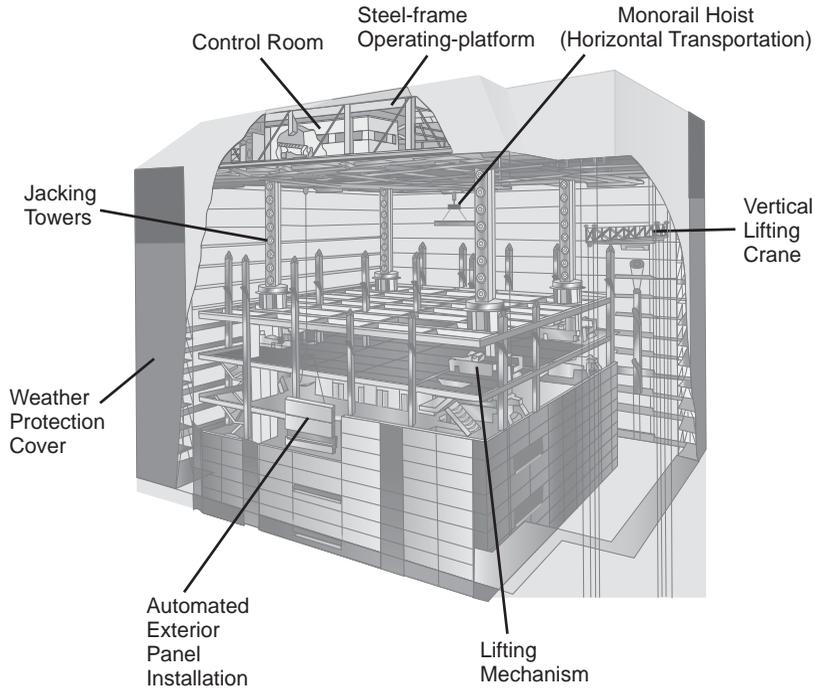


**FIGURE 6.11** Open Systems Interconnect (OSI) model developed by ISO.

4. Reliability, fault tolerance, and availability
5. Unique logic structure
6. Standard plug-in principle
7. Possible geographic distribution of communication processes
8. Cost of the system components

In an attempt to enable network communications using computers and devices from different vendors, the International Standards Organization (ISO) developed a model for LANs called the Open System Interconnect (OSI) model, which is shown in Fig. 6.11. The OSI splits the communication process into seven layers as described below:

1. **Physical layer** — The physical layer corresponds to electrical and mechanical means of data transmission. It includes coaxial cable, connectors, fiber optics, and satellite links.
2. **Data link layer** — Functions of this layer include resolution of contention for use of the shared transmission medium, delineation and selection of data addressed to this node, detection of noise, and error correction.
3. **Network layer** — This layer is responsible for establishing, maintaining, and terminating connections. Further, this layer enables internetwork routing using a global standard for assigning addresses to nodes.
4. **Transport layer** — This layer provides a network-independent service to the session, presentation, and application layers. Loss or duplication of information is also checked by this layer.
5. **Session layer** — This layer controls the dialogue between applications and provides a checkpoint and resynchronizing capability. In case of network interruptions during the communication session, this layer provides a means to recover from the failure.
6. **Presentation layer** — This layer is responsible for verifying the syntax of data exchanged between applications. Thus, it enables data exchanges between devices using different data encoding systems.
7. **Application layer** — This layer corresponds to a number of applications such as CAD/CAC systems, construction robots, NC or CNC machines, and computer graphic interfaces. This is the most complex layer and ensures that data transferred between any two applications are clearly understood [Chang et al., 1991].



**FIGURE 6.12** Shimizu's Manufacturing by Advanced Robotic Technology (SMART) system. (Source: Miyatake, Y. and Kangari, R. 1993. Experiencing Computer Integrated Construction. *Journal of Construction Engineering and Management*, ASCE. 119(2):307–323. Reproduced by permission of ASCE.)

### Example Application of Computer-Integrated Construction

The SMART system, shown in Fig. 6.12, is part of an overall CIC strategy. The SMART system integrates high-rise construction processes such as erection and welding of steel frames, placement of precast concrete floor slabs, and exterior and interior wall panel installation.

In the SMART system, steel-frame columns and beams are automatically conveyed to designated locations. Assembly of these structural components is greatly simplified by using specially designed joints.

The SMART system consists of an operating platform, jacking towers, a vertical lifting crane, and weather protection cover. The operating platform is an automated assembly system and consists of a computer-control room, monorail hoists for automated material handling, and a structural steel frame that eventually becomes the top roof of the building. Upon completion of the foundation activity, the operating platform is assembled and mounted on top of the four jacking towers of the lifting mechanism. After completion of construction work in each floor of the building, the entire automated system is lifted by vertical jacks. Thus, the automated construction work is performed, floor by floor, until the entire building is completed [Miyatake and Kangari, 1993].

## 6.5 Toward Advanced Construction Automation

In this section, four emerging technologies and equipment path planning, which can be adapted to implement cognitive or intelligent construction robots and systems, are described. Selected examples of recent applications and research on automation and robotic technologies in building construction and civil engineering works are also presented.

## Emerging Technologies

There are several emerging technologies that can be adapted to implement cognitive or intelligent construction robots and systems. The intelligent construction robots and systems cannot be successful without efficient and proper real-time monitoring and controlling of inputs and outputs about environment and construction equipment itself [Kim and Russell, 2001]. Other industries, such as the mechanical and manufacturing industries, are the valuable sources of these technologies. Although some technologies from other industries are not directly suitable for the construction industry, a little modification will satisfy the needs. This section will briefly review four technologies, namely, (1) distributed artificial intelligence, (2) global positioning system (GPS), (3) sensor and sensing technology, and (4) wireless communication technology.

### Distributed Artificial Intelligence

DAI is a subfield of artificial intelligence (AI). It is concerned with solving problems by applying both artificial intelligence techniques and multiple problem solvers [Decker, 1987]. The world of DAI can be divided into two primary arenas: Distributed Problem Solving (DPS) and Multi-Agent System (MAS). Research in DPS considers how the work of solving a particular problem can be divided among a number of modules, or nodes, that cooperate at the level of dividing and sharing knowledge about the problem and about the developing solution [Smith and Davis, 1981]. In MAS, research is concerned with coordinating intelligent behavior among a collection of autonomous intelligent agents and with how they can coordinate their knowledge, goals, skills, and plans jointly to take action or to solve problems.

There are some reasons why the DAI concept is appropriate for intelligent construction systems. First, due to possible changes in the initial conditions, the replanning of almost all task execution is often necessary. Equipment breakdowns, accidents, and other unexpected conditions are some causes of changing the initial plan. DAI can provide an effective way to deal with these kinds of changes. Second, several agents that have distributed and heterogeneous functions are involved in field operation at the same time. They should perform tasks in a cooperative manner. DAI can provide insights and understanding about interaction among agents in the construction site in order to solve problems. In addition, data from these agents should be interpreted and integrated. Third, every agent has different capacity and capability. This implies that there are a great number of possible agent combinations that are time and cost effective to perform given tasks. Fourth, it is easy to decompose tasks for field operations. An example of tasks involved in earthwork operations are stripping, hauling, spreading, and compacting.

### Global Positioning System (GPS)

The global positioning system (GPS) is a worldwide satellite-based navigation system operated and maintained by the U.S. Department of Defense. GPS provides several important features, including its high position accuracy and velocity determination in three dimensions, global coverage, all-weather capability, continuous availability to an unlimited number of users, accurate timing capability, ability to meet the needs of a broad spectrum of users, and jam resistance [Leick, 1990].

Currently, GPS is used in various fields ranging from avionics, military, mapping, mining, and land surveying, to construction. One example of construction application is SiteVision™ GPS system, which is an earthmoving control system developed by Trimble Navigation Ltd. With horizontal and vertical accuracies better than 30 mm, it allows the machine operator to work to design specifications without the use of pegs, boards, or strings. This system can give the operators all the necessary direction for precise grade, slope, and path control. Planned grade is achieved in fewer passes with less rework. With the SiteVision™ GPS system, accurate earthmoving operations take less time with lower fuel and maintenance costs on large-scale earthmoving projects [Phair, 2000; Trimble Navigation Ltd., 2001]. There is another possible application for construction equipment. An equipment motion strategy for the efficient and exact path for earthwork operations can be determined by GPS position data with preplanned motion models.

## **Sensor and Sensing Technology**

A sensor is a device or transducer that receives information about various physical effects, such as mechanical, optical, electrical, acoustic, and magnetic effects and converts that information into electrical signals. These electrical signals can be acted upon by the control unit [Warszawski and Sangrey, 1985]. Construction equipment's ability to sense its environment and change its behavior on that basis is important for an automated system. Without sensing ability, construction equipment would be nothing more than a construction tool, going through the same task again and again in a human-controlled environment. Such a construction tool is commonly used for construction operation currently, and certainly has its place and is often the right economic solution. With smart sensors, however, construction equipment has the potential to do much more. It can perform given tasks in unstructured environments and adapt as the environment changes around it. It can work in dirty and dangerous environments where humans cannot work safely. The sensor technologies are used for real-time positioning, real-time data collection during operation, equipment health monitoring, work quality verification and remediation, collision-free path planning, and equipment performance measurement.

## **Wireless Communication Technology**

Wireless communication can be defined as a form of communication without using wires or fiber optic cables over distance by the use of arbitrary codes. Information is transmitted in the form of radio spectrum, not in the form of speech. So, information can be available to users at all time, in all places. The data transmitted can represent various types of information such as multivoice channels, full-motion video, and computer data [IBM Corp., 1995].

Wireless communication technology is important for the intelligent construction systems, because equipment moves from place to place on a construction site, and data and information needed should be exchanged between construction equipment agents in real time. With wireless communication technology, communication is not restricted by harsh construction environments due to remote data connection, and construction equipment agents and human operators can expect and receive the delivery information and services no matter where they are on the construction site, even around the construction site.

## **Construction Robot Path Planning**

The purpose of a path planning method for a construction robot is to find a continuous collision-free path from the initial position of the robot to its target position. Several path-planning approaches have been suggested and applied to automated navigation of construction robots.

The research on robot path planning can be categorized into two models that are based on different assumptions about the available information for planning: path planning with complete information and path planning with incomplete information. The first model assumes that a construction robot has perfect information about itself and its environment. Information, which fully describes the sizes, shapes, positions, and orientations of all obstacles in two-dimensional or three-dimensional space, is known. Because complete information is assumed, path planning is a one-time and off-line operation [Lumelsky and Stepanov, 1987; Lumelsky and Skewis, 1988]. Latombe [1991] categorizes path planning with complete information into three general approaches: road map, cell decomposition, and potential field method.

In the second model, an element of uncertainty is present, and the missing data is typically provided by some source of local information through sensory feedback using an ultrasound range or a vision module [Lumelsky and Skewis, 1988]. A robot has no information on its environment except a start position and a target position. The sensory information is used to build a global model for path planning in real time. The path planning is a continuous on-line process. The construction and maintenance of the global model based on sensory information requires heavy computation, which is a burden on the robot [Kamon and Rivlin, 1997].

There are two approaches for path planning with incomplete information based on the way the sensory information is incorporated in the path planning. One approach separates path planning from the functions of scene reconstruction. Another approach, called dynamic path planning, integrates sensory ability into the path planning function [Lumelsky and Skewis, 1988].

In the first approach, the whole environment or a part of it is reconstructed based on the sensor data, and then a path is generated using a path-planning algorithm. However, this approach requires large computational load to reconstruct and maintain the environmental model. Thus, it is difficult to implement.

Under the dynamic planning approach, the mobile robot makes a decision on its next step at each point based on the sensory information. Initially, the mobile robot moves toward the target. When the robot encounters an object, it follows the boundary of the obstacle. If a leaving condition holds, it leaves the boundary of the obstacle and resumes its movement to the target [Kamon and Rivlin, 1997]. This approach minimizes the computational load, because the robot memorizes some points such as the start, current, hit, and target points to generate its next path. Table 6.2 shows the dynamic path planning algorithms that are mostly Bug algorithm based.

**TABLE 6.2** Algorithms for Path Planning in an Unknown Environment

Researchers	Algorithms
Lumelsky and Stepanov [1987]	Bug1 and Bug2
Lumelsky and Skewis [1988]	VisBug21 and VisBug22
Lumelsky and Tiwari [1994]	Angulus
Kamon and Rivlin [1997]	DistBug
Lee et al. [1997]	Tangent
Lee [2000]	Tangent2 and CAT
Kim [2001]	SensBug

The performance of algorithms can be measured by two evaluation criteria: the total path length and path safety. Kamon and Rivlin [1997] state that path safety should be considered while evaluating path quality. They suggest that minimal distance between the robot and the surrounding obstacles from every location along the path can be used for measuring path safety. The bigger the average distance, the safer the path. However, it is difficult to do a direct comparison between algorithms, because the performance changes based on different environments.

## Examples of Recent Research and Applications

### Building Construction Domain

From the late 1980s, Japanese contractors began to explore the application of manufacturing principles to construction, because they began to understand that single-task automation could not provide big payoffs. By 1991, they achieved the first full-scale application of construction automation for building construction [Cousineau and Miura, 1998]. Some construction automation systems are listed in Table 6.3. These systems adapt the just-in-time principle for material delivery, bar-coding technology for tracking and placing delivered materials, and information technology for monitoring and coordinating construction processes. In these systems, the numbers of single-task robots are used, efforts for integrating single-task robots are made, and more construction processes are automated. These construction systems have four fundamental elements: an on-site factory protected by an all-weather enclosure, an automated jacking system, an automated material-conveying system, and a centralized information-control system [Cousineau and Miura, 1998].

### Civil Engineering Works Domain

Many of the recently developed systems for civil works are intelligent assistant tools that enhance operators' ability to sense, plan, and monitor their works in real time. These tools integrate human operators and construction machines into a whole effective construction system. Tele or automated systems may be the only feasible alternative, when construction operations are performed in hazardous environments. In many cases, the cost of protecting human operators or workers may exceed the cost of developing tele or automated systems.

**TABLE 6.3** Construction Automation Systems for Building Construction

System Description	Project Year	Company
Push-Up	1989–91, 1993–95	Takenaka Co., Japan
SMART (Shimizu Manufacturing System by Advanced Robotics Technology)	1991–94, 1994–97	Shimizu Co., Japan
ABCS (Automated Building Construction System)	1991–94	Obayashi Co., Japan
T-Up (Totally Mechanized Construction System)	1992–94	Taisei Co., Japan
MCCS (Mast Climbing Construction System)	1992–94, 1995–98	Maeda Co., Japan
AKWTSUKI 21 (Automated weather-unaffected building construction system)	1994–96	Fujita Co., Japan
AMURAD (Automatic Up-Rising Construction by Advanced Technique)	1995–96	Kajima Co., Japan
Big Canopy	1995–97	Obayashi Co., Japan

Source: Modified from Cousineau and Miura, 1998.

### ***Semiautonomous Dump Truck System***

To overcome worker shortage problems and to prevent accidents on heavy construction sites, an autonomous dump truck system was developed by Saito et al. [1995]. The aim of HIVACS is to develop a semiautonomous dump truck system that has adaptability for changing surroundings such as long-distance driving, high-speed driving, driving within road width, and change of route, etc., with comprehensive peripheral facilities. According to the report, this system enables two operators to manage five dump trucks without truck drivers and results in a labor saving 17% at the studied dam construction site.

### ***Tele-Earthwork System***

Sakoh et al. [1996] developed the Tele-Earthwork System to provide a fail-safe, automated system to assist both older and unskilled laborers, and to save labor. It is a remote-control system that can perform a series of earthwork functions such as digging, loading, transporting, and disposal. In this system, an earthwork equipment control room is installed at a safe location away from the harmful and dangerous environment. An operator performs a series of earthwork tasks in the control room while observing equipment status and in-process tasks through three-dimensional images on the screen. All information is transmitted via a mobile radio relay car. This proposed system was applied to a full-scale earthwork project.

### ***Automated Landfill System***

A conceptual framework for an automated landfill system (ALS) was developed by Tserng et al. [1996], Tserng [1997], and Tserng et al. [2000]. The research focused on space model development and management, mapping and positioning methods, and equipment motion planning. The properties and location of job-site space are recorded into nodes of the quadtree data structure. In order to avoid collision with obstacles and other equipment, which are transformed to represent the locus of forbidden positions, the equipment becomes a point in the transformed geometric model called configuration space (Cspace). The quadtree-cube geometric model is employed for recording several Cspace in one quadtree structure. After the quadtree-cube system is established, the specific quadtree network is extracted for each piece of equipment. Then, this system uses the k-shortest path algorithm to traverse the quadtree network.

### ***Autonomous Excavator***

A pure autonomous excavator is being developed by Carnegie Mellon University. The range of automation covers the whole excavation process from bucket path planning to material dump on a truck. It has a high-level planner that determines where and how to excavate, and a local-optimal planner that decides the shape of each dig [Stentz et al., 1998].

### ***GPS-Based Guiding System***

Pampagnin et al. [1998] developed an operator-aiding system for the real-time control of the positioning of road construction compactors. The main goal of this system was to assist the compactor operator in the road compaction task, by helping him to perform the exact number of passes, at the right speed,

everywhere on the surface to be compacted. GPS, optical fiber gyrometer, and advanced filtering techniques were used for a civil engineering machine for the first time.

### ***Computer Integrated Road Construction***

Peyret [1999] and Peyret et al. [2000] conducted a study on the computer integrated road construction (CIRC) project that aims to develop CIC systems for the real-time control and monitoring of task operations performed by road construction equipment. These systems mainly rely on CAD data established during the design phase and during the construction in real time. CIRC products, the one for the compactors and the one for the asphalt pavers, can provide good tools for operator assistance, machine control, and quality assessment and ensuring. They showed the benefits of new technologies applied to road construction works.

### ***Laser-Based System***

Haoud [1999] described a laser-based system for earthwork applications. On the construction machine and on both sides of the blade, electric receivers are installed on two guide masts that send signals to the control system to notify the status of the blade. The construction machine is equipped with a manual checking device, which is used for machine calibration and checking operation results, and a swivel-head laser emitter, which defines a virtual plane. This virtual plane is parallel to the future plane for the pavement. The laser-based system offers the quality improvement of the end result due to lower tolerance levels and better evenness of the surface. With this system, it is possible to save manpower significantly and increase productivity greatly.

### ***Automated System for Quality Control of Compaction Operations***

In road construction, the number of passes of compactors will directly affect the density of asphalt pavement, when roller frequency, wheel load, and compactor speed are kept constant. For this reason, monitoring the exact number of passes over the entire surface of pavement is important. An automated system for mapping compaction equipment using GPS technology and an algorithm was developed. It can find the exact number of passes at each point in the roadway and graphically depict the number of passes of compactors (Oloufa et al., 1999).

### ***Automated Earthmoving Status Determination***

Present research conducted by the National Institute of Standards and Technology (NIST) is focused on developing automated, nonintrusive production-measurement systems and procedures for monitoring the status of general earthmoving operations. The effort of the research includes the development of methods for automated registration of 2–1/two-dimensional range data, for automated volume calculation, and for web-based three-dimensional site simulators. Information on terrain changes in one location is sent via wireless Ethernet to another location to display the instant terrain geometry and to perform cut and fill calculations [Stone et al., 2000].

### ***Open Communication System***

Recently, information technology and communication technology have been rapidly expanding and growing. They offer better possibilities for automation and robotization in earthmoving and road construction. The effective and efficient automation with mobile construction equipment can be possible by effective data communication between electronic components and systems equipped with mobile construction machines. The University of Magdeburg, Germany, conducted a study on an open communication system (CANopen) for mobile construction equipment, which offers higher flexibility and extensive safety and control mechanisms. As a result of the integrated connection among sensors, actuators, and electronic systems, new possibilities are created for automation and robotization in construction [Poppy and Unger, 2000].

### ***Computer Aided Earthmoving System (CAES)***

There is a commercially available system for assisting human operators, a Computer Aided Earthmoving System (CAES) introduced by Caterpillar Inc. (2001). CAES integrates planning and design operations.

CAES consists of on-board computers, software, GPS, and data radios and receivers, which replace the manpower and time-intensive processes associated with conventional surveying. CAES allows engineers to transmit planning and designs wirelessly to the machine's on-board computer. The machine operator can get information on where the machine is in the design area, what the current surface is, and where the final surface is. The operator uses this information to see where to cut and fill and by how much. The machine progress is measured and recorded to update information for the operator and is transmitted to the office for analysis and documentation. Caterpillar is continuing to develop advanced technology products. These products include radio data communications, machine monitoring, diagnostics, job and business-management software, and machine control that can be used for automated construction systems.

***Intelligent Earthwork System***

Kim [2001] developed a framework for an intelligent earthwork system (IES). This framework defines the architecture and methodologies to serve as the foundation for developing an IES. The IES enables multiple pieces of equipment to automatically generate earthwork plans for construction robots and perform the given operations. The proposed framework defines the architecture and methodologies to serve as the foundation for developing an IES, such as a construction agent model for IES, a task identification and planning method for effective task execution, a resource allocation method in order to maximize equipment utilization, and a dynamic path planning algorithm to avoid collisions in the construction site.

## 6.6 Economics

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Three major factors contributing to economic benefits of construction automation are productivity, quality, and savings in skilled labor [Kangari and Halpin, 1989]. These benefits must be weighed against the costs of automation, including initial investment and operating costs; these are further described in Table 6.4. Economic data resulting from analyses of several robot applications and automated systems are described below.

### Automated Stone Cutting

Benefits of a partially automated stone-cutting mill were assessed through computer simulation [Hijazi et al., 1988]. In comparison to traditional stone-cutting methods, simulation of the automated system resulted in a 74% increase in productivity and 42% less time to process identical orders.

### Steel Bridge Deck Welding

The economic implications of using robot welders in steel bridge deck fabrication were studied by Touran and Ladick [1988]. Using the robot welders in the fabrication shop was predicted to reduce fabrication costs by 5.6%.

**TABLE 6.4** Costs Associated with Construction Robotics

Initial Investment Costs	Robot Operating Costs
Research and development	On-site programming
Engineering personnel	Software adaptation
Product testing	Labor cost (technicians)
Robot components	Electricity
Control hardware	System dismantling and re-setup
	Robot transporting costs
	Maintenance and repair

## **Excavation**

Most reports related to construction automation indicate improvement in productivity and quality. In one particular instance, the development and use of partially automated laser-guided grading equipment not only improved productivity of fine grading operations, but also increased the contractor's flexibility in managing its fleet. The contractor gained a major competitive advantage that contributed to the contractor's growth from an annual volume of \$500,000 in 1976 to over \$50,000,000 in 1984 [Tatum and Funke, 1988].

## **Large-Scale Manipulators**

Use of large-scale manipulators (LSMs) can reduce the amount of non-value-added tasks and increase productivity. According to a case study by the Construction Industry Institute, LSMs have high potential for industrial construction. They can be used for elevated concrete placement, painting, and sandblasting, as well as pipe, cable tray, and structural steel erection. These tasks on average constitute 33% of total project work-hours [Hsieh and Haas, 1993].

Results from a productivity analysis performed by videotaping identical pipe-handling operations by a pipe manipulator and a telescopic rough-terrain crane indicate a shorter cycle time for the pipe manipulator [Hsieh et al., 1993].

## **Interior Finishing Robot**

A performance study of an interior-finishing robot indicated that the net productivity of the robot can reach 10–19 m<sup>2</sup>/h in a one-layer coating and 8–8.5 m<sup>2</sup>/h in a dry (mortarless) building. These figures are four to five times higher than for an average construction worker. Wages of \$25 per hour, 1500 to 2000 hours of robot usage per year, suitable site conditions, and proper organization of material packaging can result in savings of 20 to 50% in the cost of interior finishing work [Warszawski and Navon, 1991; Warszawski and Rosenfeld, 1993].

## **Exterior Building Finishers**

Results from an outdoor experiment using a tile-setting robot indicate a setting efficiency of 14 m<sup>2</sup>/day, with an average adhesive strength of 17.2 kg/cm, representing improved productivity and quality [Kikawada et al., 1993].

## **Automated Slab Placing and Finishing**

According to a study on automated concrete placement and finishing [Moselhi et al., 1992], automation of placing and finishing concrete slabs would require a minimum annual work volume of 144,321 m<sup>2</sup> (1,600,000 ft<sup>2</sup>) of pavement in order to be more economical than the conventional manual process. Thus, at present, the sizable capital cost of the initial investment precludes smaller paving contractors from considering automation.

## **Shimizu's SMART System**

Shimizu Corporation's experience with the SMART system includes improved productivity, attractive working environment, all-weather protection, higher quality and durability, reduced construction schedule duration, and reduced amount of waste and damage to materials. Upon further advancement of the SMART system, a 50% reduction in construction duration is expected [Miyatake and Kangari, 1993].

## **Obayashi's ABCS**

The evaluation of ABCS system shows that when cranes were operated automatically, a 30% reduction in power was achieved. During construction, sound measurement indicated a marked improvement in

the work environment at the factory floor level. The work environment was also improved by the all-weather sheeting [Cousineau and Miura, 1998].

### **Maeda's M CCS**

Observations made during construction included 30% reduction in manpower, significant reduction in waste, and 20% reduction in the cycle time to complete one story. As workers learn how to use the M CCS, more reduction in manpower and schedule is expected [Cousineau and Miura, 1998].

### **Obayashi's Big Canopy**

Big Canopy is the first automated system to improve overall productivity. Use of this system resulted in 60% reduction in labor for frame erection and reduction in material cost [Cousineau and Miura, 1998].

### **Kajima's AMURAD**

According to observations on the use of AMURAD, significant improvement is achieved: (1) 30% reduction in construction time, (2) 50% reduction in manpower, (3) 50% reduction in waste, (4) more predictable schedule by using the all-weather protective sheeting, and (5) more comfortable environment for workers [Kajima Corporation, 1996].

## **6.7 Summary**

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A brief description of construction industry characteristics followed a discussion on the importance of construction automation. Fixed construction automation was defined, and selected examples of fixed construction automation were provided. Following this, programmable automation including robotic and numerical control applications were described. Computer-integrated construction (CIC), which provides an intelligent approach to planning, design, construction, and management of facilities, requires emerging technology that encompasses research efforts from a variety of engineering and computer science disciplines. A detailed description of CIC and supporting areas that play important roles in implementing CIC was provided. Some emerging technologies and equipment path planning, which can be adapted to implement cognitive or intelligent construction robots and systems, are described. Finally, selected examples of recent applications and research on automation and robotic technologies in building construction and civil engineering works are presented.

### **Defining Terms<sup>1</sup>**

**Electronic controls** — Computer-based hardware units designated to control and coordinate the positions and motions of manipulator arms and effectors. A controller is always equipped with manipulator control software, enabling an operator to record a sequence of manipulator motions and subsequently play back these motions a desired number of times. More sophisticated controllers may plan entire sequences of motions and tool activators given a desired work task.

**End effectors** — Tools and devices on automated construction equipment, including discharge nozzles, sprayers, scrapers, grippers, and sensors. The robot tools are usually modified compared with tools used by human workers or even specially designed to accommodate unique characteristics of the working machine.

**Manipulators** — Stationary, articulated arms that are essential components of industrial robotics. The role of a manipulator arm is to move an effector tool to the proper location and orientation

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<sup>1</sup>Source: Adapted from Hunt, V.D. 1983. *Industrial Robotics Handbook*. Industrial Press, New York.

relative to a work object. To achieve sufficient dexterity, arms typically require six axes of motions (i.e., six degrees of freedom), three translational motions (right/left, forward/back, up/down), and three rotational motions (pitch, roll, and yaw).

**Motion systems** — Systems that enable the essential features of mobility and locomotion for construction equipment. A variety of mobile platforms can support stationary manipulator arms for performance of required tasks. An example selection of automatically guided vehicle (AGV) platforms is presented in Skibniewski [1988]. However, most automated tasks supported by AGVs in construction will require modified control systems and larger payloads than those in automated factories.

**Sensors** — A device for converting environmental conditions into electrical signals. An environmental condition might be a mechanical, optical, electrical, acoustic, magnetic, or other physical effect. These effects may occur with various levels of intensity and can be assessed quantitatively by more sophisticated sensors. These measurements are used to control robot movements and, in advanced robots, to plan operations. Sensors are important to robotics in construction because they instantaneously convey elements of the building environment to the control unit.

## References

- Bell, L.C. and McCullough, B.G. 1988. *Bar Code Application in Construction*. A Report to the Construction Industry Institute, SD-33, University of Texas, Austin. February.
- Bernold, L.E., Altobelli, F.R., and Taylor, H. 1992. Computer-controlled brick masonry. *J. Comput. Civ. Eng., ASCE*. 6(2):147–161.
- BLS. 2000a. National Census of Fatal Occupational Injuries in 1999. *NEWS*, Bureau of Labor Statistics, <http://stats.bls.gov/>.
- BLS. 2000b. Workplace Injuries and Illnesses in 1999. *NEWS*, Bureau of Labor Statistics, <http://stats.bls.gov/>.
- BLS. 2001. Employment Situation Summary. Bureau of Labor Statistics, <http://stats.bls.gov/news.release>.
- Business Roundtable. 1982. *Improving Construction Safety Performance*, Construction Industry Cost Effectiveness Report. Business Roundtable, New York.
- Caterpillar Inc. 2001. *Computer Aided Earthmoving Systems (CASE)*. Caterpillar Inc., <http://www.caterpillar.com/>.
- Chang, T., Wysk, R.A., and Wang, S. 1991. *Computer-Aided Manufacturing*. Prentice Hall, Englewood Cliffs, NJ.
- Cherneck, J., Logcher, R., and Sriram, D. 1991. Integrating CAD with Construction Schedule Generation. *J. Comput. Civ. Eng., ASCE*. 5(1):64–86.
- Cleveland, A.B. and Francisco, V. 1988. Use of Real-Time Animation in the Construction Process. *Transp. Res. Rec.* 1186:5–39.
- Considine, D.M. and Considine, G.D. 1986. *Standard Handbook of Industrial Automation*. Chapman & Hall, New York.
- Cousineau, L. and Miura, N. 1998. *Construction Robots: The Search for New Building Technology in Japan*, ASCE Press, Reston, VA.
- Decker, K. 1987. Distributed Problem-Solving Techniques: A Survey. *IEEE Trans. Syst., Man Cyber., SMC* 17:729–740.
- Everett, J.G. and Saito, H. 1996. Construction Automation: Demands and Satisfiers in the United States and Japan. *J. Constr. Eng. Manage., ASCE*. 122(2):147–151.
- Fisher, D.J. and O'Connor, J.T. 1991. Constructability for Piping Automation: Field Operations. *J. Constr. Eng. Manage., ASCE*. 117(3):468–485.
- Foley, J.D. and Van Dam, A.V. 1982. *Fundamentals of Interactive Computer Graphics*. Addison-Wesley, Reading, MA.
- Groover, M.P., Parriera, N.D., Doydum, C., and Smith, R. 1989. A Survey of Robotics Technology in Construction. *SME Tech. Pap.* May 7–11, 1–20.

- Hanser, C. 1999. Fully Automated Masonry Plant, *Proc. 16<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Madrid, Spain, 295–300.
- Haoud, H. 1999. Laser Technology Applied to Earthworks. *Proc. 16<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Madrid, Spain, 33–40.
- Hendrickson, C. and Au, T. 1988. *Project Management for Construction: Fundamental Concepts for Owners, Engineers, Architects and Builders*, p. 486. Prentice Hall, Englewood Cliffs, NJ.
- Hijazi, A., AbouRizk, S., and Halpin, D.W. 1988. *Impact of Automation on Construction Fixed Plant Operations*. Technical Report. Purdue University, West Lafayette, IN.
- Hinze, J.W. 1997. *Construction Safety*, Prentice-Hall, Inc., Englewood Cliffs, NJ.
- Horning, C. and Kinura, H. 1993. Three-Dimensional FEM analysis with Graphical Interface. *Proc. 5<sup>th</sup> Int. Conf. Comput. Civ. Build. Eng.* Anaheim, CA, pp. 1283–1290.
- Hsieh, T. and Haas, C. 1993. Applications of Large-Scale Manipulators in the Construction Environment. *Proc. 10<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Houston, TX, 55–62.
- Hsieh, T.Y., Fulton, C., Gibson, G.E., and Haas, C.T. 1993. An Evaluation of the Pipe Manipulator Performance in a Material Handling Yard. *Proc. 10<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Houston, TX, 55–62.
- Hughes, P.J., O'Connor, J.T., and Traver, A.E. 1989. Pipe Manipulator Enhancements for Increased Automation. *J. Constr. Eng. Manage.*, ASCE. 115(3):412–423.
- Hunt, V.D. 1983. *Industrial Robotics Handbook*. Industrial Press, New York.
- IBM Corp. 1995. *An Introduction to Wireless Technology*, IBM International Technical Support Organization, Research Triangle Park, NC.
- Jaselskis, E.J. and Anderson, M.R. 1994. On Hazardous Waste and Robotic Applications. *J. Environ. Eng.*, ASCE. 120(2):359–378.
- Kajima Corporation. 1996. 9-Story Company Housing is Under Construction Using a Fully Automated System Called AMURAD. Kajima Press Release, Tokyo, Japan.
- Kamon, I. and Rivlin, E. 1997. Sensory-Based Motion Planning with Global Proofs. *IEEE Trans. Robot. Automat.*, 13(6): 814–822.
- Kangari, R. and Halpin, D.W. 1989. Potential Robotics Utilization in Construction. *J. Constr. Eng. Manage.*, ASCE. 115(1):126–143.
- Kikawada, K., Ashikaga, S., Ishikawa, S., and Nishigaki, S. 1993. Practical Tile-Setting Robot for Exterior Walls. *Proc. 10<sup>th</sup> Int. Symp. Automat. Robot. Constr.* Houston, TX, 71–75.
- Kim, S.K. 2001. *Toward a Framework for an Intelligent Earthwork System*. Ph.D. Thesis, University of Wisconsin-Madison, Madison, WI.
- Kim, S.K., and Russell, J. S. 2001. Framework for an Intelligent Earthwork System: Part 1 — System Architecture, *Automation in Construction* (In press).
- Kunigahalli, R. and Russell, J.S. 1995. Framework for Development of CAD/CAC Systems. *Automation in Construction*, 3: 327–340.
- Kunigahalli, R., Russell, J.S. and Veeramani, D. 1995. Extracting Topological Relationships from a Wire-Frame CAD Model. *J. Comput. Civ. Eng.*, ASCE. 9(1):29–42.
- Latombe, J. 1991. *Robot Motion Planning*, Kluwer Academic Publishers, Boston, MA.
- Lee, S. 2000. *Spatial Model and Decentralized Path Planning for Construction Automation*. Ph.D. Thesis, University of Wisconsin-Madison, Madison, WI.
- Lee, S., Adams, T.M., and Ryoo, B. 1997. A Fuzzy Navigation System for Mobile Construction Robots. *Automation in Construction*, 6: 97–107.
- Leick, A. 1990. *GPS Satellite Surveying*, John Wiley & Sons, New York.
- Levitt, R.E. and Samelson, N.M. 1993. *Construction Safety Management*, John Wiley and Sons, Inc., New York.
- Luggen, W.W. 1984. *Fundamentals of Numerical Control*. Delmar, Albany, NY.
- Lum, S.K.S. and Moyer, B.C. 2000. Gross Domestic Product by Industry for 1997–99. *Survey of Current Business*, Bureau of Economic Analysis, 24–45.
- Lumelsky, V.J. and Skewis, T. 1988. A Paradigm for Incorporating Vision in the Robot Navigation Function. *IEEE Int. Conf. Robot. Automat.*, 2, Philadelphia, PA, 734–739.

- Lumelsky, V.J. and Stepanov, A.A. 1987. Path-Planning Strategies for a Point Mobile Automaton Moving Amidst Unknown Obstacles of Arbitrary Shape. *Algorithmica*, 2: 403–430.
- Lumelsky, V.J. and Tiwari, S. 1994. An Algorithm for Maze Searching with Azimuth Input. *IEEE Int. Conf. Robot. Automat.*, 1, San Diego, CA, 111–116.
- Maynard, H.B. 1971. *Industrial Engineering Handbook*. McGraw-Hill, New York.
- Miyatake, Y. and Kangari, R. 1993. Experiencing Computer Integrated Construction. *J. Constr. Eng. Manage.*, ASCE. 119(2):307–323.
- Morad, A.A., Cleveland, A.B., Beliveau, Y.J., Francisco, V.D., and Dixit, S.S. 1992. Path Finder: AI-Based Path Planning System. *J. Comput. Civ. Eng.*, ASCE. 6(2):114–128.
- Mortenson, M.E. 1985. *Geometric Modeling*. John Wiley & Sons, New York.
- Moselhi, O., Fazio, P., and Hanson, S. 1992. Automation of Concrete Slab-on-Grade Construction. *J. Constr. Eng. Manage.*, ASCE. 118(4):731–748.
- Motazed, B. and Whittaker, W.L. 1987. *Automated Pipe Mapping*. The Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA. March.
- O'Connor, J. T., Traver, A.E., and Tucker, R.L. 1987. Research into Automated Piping Construction. *Proc. 4<sup>th</sup> Int. Symp. Robot. Artif. Intel. Build. Constr.* Building Research Station, Haifa, Israel. June, 268–273.
- Oloufa, A.A., Do, W., and Thomas, H.R. 1999. An Automated System for Quality Control of Compaction Operations: Receiver Tests & Algorithms. *Proc. 16<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Madrid, Spain, 67–71.
- Pampagnin, L., Martinez, F., Peyret, F., Backlund, K., Fliedner, J., Gorham, B., Marchand, J., and Becker, J. 1998. A New GPS-Based Guiding System for Compactors. *Proc. 15<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Munich, Germany, 153–162.
- Paulson, B.C. 1985. Automation and Robotics for Construction. *J. Constr. Eng. Manage.*, ASCE. 111(3):190–207.
- Peyret, F. 1999. The Computer Integrated Road Construction Project. *Proc. 16<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Madrid, Spain, 593–598.
- Peyret, F., Jurasz, J., Carrel, A., Zekri, E., and Gorham, B. 2000. The Computer Integrated Road Construction Project. *Automation in Construction*, 9:447–461.
- Phair, M. 2000. Satellite Positioning System Moves from Dozers to Motor Graders. *ENR*, 244(12):49.
- Point, G. 1988. Two Major Innovations in Current Maintenance: The Multipurpose Vehicle and the Integrated Surface Patcher. *67<sup>th</sup> TRB Annu. Meet.*, Transportation Research Board, Washington, D.C., 29.
- Poppy, W. and Unger, E. 2000. CANopen for Mobile Construction Machines — An Open Communication Network for Control and Automation. *Proc. 17<sup>th</sup> Int. Symp. Automat. Robot. Constr.*, Taipei, Taiwan, 515–518.
- Rehg, J. A. 1992. *Introduction to Robotics in CIM Systems*. Prentice Hall, Englewood Cliffs, NJ.
- Reinschmidt, K.F., Griffs, F.H., Browner, P.L. 1991. Integrated Engineering, Design, and Construction. *J. Constr. Eng. Manage.*, ASCE. 117(4):756–772.
- Rembold, V., Bleme, C., and Dillmann, R. 1985. *Computer-Integrated Manufacturing Technology and Systems*. Marcel Dekker, New York.
- Requicha, A.A.G. 1980. Representations of Rigid Solids: Theory, Methods, and Systems. *ACM Comp. Surv.* 12(4):439–465.
- Requicha, A.A.G. and Rossignac, J.R. 1992. Solid Modeling and Beyond. *IEEE Comp. Graph. Appl.* September, 31–44.
- Reymendt, J. and Worner, J.D. 1993. Object-Oriented Modeling of Concrete Structures. *Proc. 5<sup>th</sup> Int. Conf. Comput. Civ. Build. Eng.* Anaheim, CA, 86–93.
- Sagawa, Y. and Nakahara, Y. 1985. Robots for the Japanese Construction Industry. *IABSE Proceedings*. May, 86.
- Saito, M. 1985. *The Development of a Mobile Robot for Concrete Slab Finishing*. Technical Report. Mechanical Engineering Development Dept., Kajima Co., Tokyo, Japan.

- Saito, H., Sugiura, H., and Yuta, S. 1995. Development of Autonomous Dump Trucks System (HIVACS) in Heavy Construction Sites. *Proc. 1995 IEEE Int. Conf. Robot. Automat.*, Aichi, Japan, 2524–2529.
- Sakoh, S., Okano, M., Kita, S., and Okumatsu, T. 1996. Development and Practice of the Tele-Earthwork System. *Advanced Robotics*, 10(4): 425–438.
- Sanvido, V.E. and Medeiros, D.J. 1990. Applying Computer-Integrated Manufacturing Concepts to Construction. *J. Constr. Eng. Manage.*, ASCE. 116(2):365–379.
- Sherman, P.J. 1988. Japanese Construction R&D: Entrée into U.S. Market. *J. Constr. Eng. Manage.*, ASCE. 114(1):138–142.
- Skibniewski, M.J. 1988. *Robotics in Civil Engineering*, Van Nostrand Reinhold, New York.
- Skibniewski, M.J. and Russell, J.S. 1989. Robotic Applications to Construction. *Cost Eng.* 31(6):10–18.
- Slocum, A.H., Laura, D., Levy, D., Schena, B., and Ziegler, A. 1987. Construction Automation Research at the Massachusetts Institute of Technology. *Proc. 4th Int. Symp. Robot. Artif. Intel. Build Constr.* Building Research Station, Haifa, Israel. June, 222–233.
- Smallwood, J. and Haupt, T.C. 2000. Safety and Health Team Building. *Construction Safety and Health Management*, Prentice-Hall Inc., Englewood Cliffs, NJ.
- Smith, R.G. and Davis, R. 1981. Framework for Cooperation in Distributed Problem Solving. *IEEE Trans. Syst., Man Cyber.*, SMC. 11(1):61–70.
- Stentz, A., Bares, J., Singh, S., and Rowe, P. 1998. A Robotic Excavator for Autonomous Truck Loading. *Proc. 1998 IEEE/RSJ Int. Conf. Intel. Robot. Syst.*, Victoria, B.C., Canada, 1885–1893.
- Stone, W.C., Cheok, G., and Lipman, R. 2000. Automated Earthmoving Status Determination. *Robotics 2000, Proc. 4th Int. Conf. Expo./Demon. Robot. Chall. Situa. Envir.*, Albuquerque, NM, 111–119.
- Stukhart, G. and Berry, W.D. 1992. *Evaluation of Voice Recognition Technology*. Report to Construction Industry Institute, SD-76. University of Texas, Austin. June.
- Sugiyura, H., Yute, S., Nishide, K., Hatekeyama, O., and Nishigaki, S. 1993. Autonomous Dump Trucks Systems for Transporting and Positioning Heavy-Duty Materials in Heavy Construction Sites. *Proc. 10th Int. Symp. Automat. Robot. Constr.* Houston, TX, 253–260.
- Tatum, C.B. and Funke, A.T. 1988. Partially Automated Grading: Construction Process Innovation. *J. Constr. Eng. Manage.*, ASCE. 114(1):19–35.
- Technical Specifications for Miller Formless Systems, Automated Slip Forming Systems, Bulk Cement and Unloading Systems. 1988. Miller Formless Systems Co., McHenry, IL.
- Technical Specifications of the John Deere 690C Excavator. 1985. John Deere, Inc. Moline, IL. August.
- Teicholz, E. and Orr, J.N. 1987. *Computer-Integrated Manufacturing Handbook*. McGraw-Hill, New York.
- Terauchi, S., Miyajima, T., Mirjamoto, T., Arai, K., and Takiwaza, S. 1993. Development of an Exterior Wall Painting Robot — Capable of Painting Walls with Indentations and Protrusions. *Proc. 10th Int. Symp. Automat. Robot. Contr.* Houston, TX, 285–292.
- Touran, A. and Ladick, D. 1988. Applications of Robotics on Bridge Deck Fabrication. *J. Constr. Eng. Manage.*, ASCE. 115(1):35–52.
- Trimble Navigation Ltd. 2001. <http://www.trimble.com/>.
- Tserng, H.P. 1997. *Towards a Framework for an Automated Landfill System (ALS)*. Ph.D. Thesis, University of Wisconsin-Madison, Madison.
- Tserng, H.P., Ran, B., and Jeffrey, S.R. 2000. Interactive Path Planning for Multi-Equipment Landfill Operations, *Automation in Construction*, 10(1):155–168.
- Tserng, H.P., Veeramani, Kunigahalli, R., and Russell, J.S. 1996. OPSALC: A Computer-Integrated Operations Planning System for Autonomous Landfill Compaction, *Automation in Construction*, 5(1):39–50.
- Tucker, R.L. 1990. Construction Automation in the United States. *Proc. 7th Int. Sympo. Automat. Robot. Constr.*, Bristol, England.
- Uchino, T., Narisawa, J., Sato, Y., and Kumazawa, K. 1993. Multi-Jointed Pile Driving Machine with a Computer-Assisted Guiding System. *Proc. 10th Int. Symp. Automat. Robot. Constr.* Houston, TX, 363–370.
- Veeramani, D., Tserng, H.P., and Russell, J.S. 1998. Computer-Integrated Collaborative Design and Operation in the Construction Industry, *Automation in Construction*, 7(6):485–492.

- Warszawski, A. 1990. *Industrialization and Robotics in Building: A Managerial Approach*. Harper & Row, New York.
- Warszawski, A. and Navon, R., 1991. Robot for Interior-Finishing Works. *J. Constr. Eng. Manage.*, ASCE. 117(3):402–422.
- Warszawski, A. and Navon, R. 1998. Implementation of Robotics in Building: Current Status and Future Prospects. *J. Constr. Eng. Manage.*, ASCE. 124(1):31–41.
- Warszawski, A. and Rosenfeld, Y. 1993. Feasibility Analysis of Robotized vs. Manual Performance of Interior Finishing Tasks. *Proc. 10<sup>th</sup> Symp. Automat. Robot. Constr.* Houston, TX, 383–390.
- Warszawski, A. and Sangrey, D.A. 1985. Robotics in Building Construction. *J. Constr. Eng. Manage.*, ASCE. 111(3): 260–280.
- Webster, A.C. 1993. Japanese Building Design and Construction Technology. *J. Prof. Issues Eng. Educ. Prac.*, ASCE. 119(4):358–377.
- Whittaker, W.L. 1985a. *REX: A Robot Excavator*. The Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA. August.
- Whittaker, W.L. 1985b. *Terregator*. Technical Report. The Robotics Institute, Carnegie-Mellon University, Pittsburgh, PA. August.
- Yoshida, T. and Ueno, T. 1985. *Development of a Spray Robot for Fireproof Treatment*, 48–63. Shimizu Technical Research Bulletin 4. Tokyo, Japan.

## Further Information

Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC) provide information on the latest developments in the field of construction automation. The *International Journal of Automation in Construction*, the *ASCE Journal of Computing in Civil Engineering*, and the *ASCE Journal of Construction Engineering and Management* document the advances in computer-integrated construction.

The following books provide a basic introduction to construction robotics: *Robotics in Civil Engineering* by M. J. Skibniewski, *Industrialization and Robotics in Building: A Managerial Approach* by A. Warszawski, and *Construction Robots: The Search for New Building Technology in Japan* by L. Cousineau and N. Miura.