47. Robotics in Construction

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This chapter introduces various construction automation concepts that have been developed over the past few decades and presents examples of construction robots that are in current use (as of 2006) and/or in various stages of research and development. Section 47.1 presents an overview of the construction industry, which includes descriptions of the industry, the types of construction, and the typical construction project. The industry overview also discusses the concept of *automation* versus *robotics* in construction and breaks down the concept of robotics in construction into several levels of autonomy. Section 47.1 also presents traditional and advanced concepts for sensing systems in construction, which enable the use of robots and various forms of automation. Section 47.2 discusses some of the economic aspects of implementing robotics in construction, and Sect. 47.3 presents examples of robots from various construction applications. Section 47.4 discusses unsolved technical problems in construction robotics, which include interoperability, connection systems, tolerances, and power and communications. Finally, Sect. 47.5 discusses future directions in construction robotics and Sect. 47.6 gives some conclusions and suggests resources for further reading.

Construction is a ubiquitous human activity that relates to the creation or realization of physical artifacts or custom-made capital goods. It is distinguished from manufacturing in that the production activity normally occurs in a field setting and is undertaken in the open air, on natural terrain, and often with naturally occurring materials. Typically, building and construction products are large in scale and unique in form. Moreover, the environment or field setting is typically unique and requires a, rather ad hoc, *factory* to be synthesized on site.

Over the centuries, various forms of machines and mechanical engineering systems have been introduced into the construction engineering domain and into the building and construction industry to increase production efficiency. In common with the fields of agriculture, mining, and forestry, the long-term trend has been for these fields to become increasingly mechanized [47.1].

In the last few decades, with the decrease in the relative cost of machinery to labor and with the globalization of markets, the construction industry has become significantly more capital intensive and large-scale machinery systems and pieces of construction plant – such as tunnel-boring machines and very large tower cranes – have become commonplace. This trend to mechanization is likely to continue with the progressive introduction of computer-controlled construction machinery and flexible manufacturing concepts into the industry.

With the relatively recent development of the microprocessor and the availability of low-cost computer and sensing technology, construction robots have become a technical and economic possibility and this form of technology is now gradually being used in the industry.

47.1 Overview

The application of robots in construction traditionally falls under *construction automation*. As the term implies, the field of construction automation is focused on automating construction processes, and the use of robots is but one aspect of automation. Construction processes also fall within several categories best described through a brief introduction to the construction industry.

47.1.1 Industry Description

In the USA the value of construction put in place in 2002 was approximately 8% of the national gross domestic product (GDP) [47.2], employing over 7 million workers in 2005 [47.3]. According to data from a 2003 US Census Bureau report, approximately half (48.25%) of those workers were employed by firms of four employees or fewer, and roughly 60% of all construction workers worked for specialty trade contractors who accounted for roughly 60% of construction firms [47.4] (specialty trade contractors are usually subcontractors on a project and are not responsible for the overall outcome of the project). In the European Union (EU), construction accounted for 5.7% of the EU's gross value added in 2004, and the construction industry employed over 11 million workers [47.5]. Worldwide, construction industry *spending* is estimated at approximately 11% of the world's GPD [47.6].

Construction is considered by many to be technologically behind other industries, such as manufacturing. In manufacturing, a product is designed for mass production, whereas construction *products* (or projects) are usually one-off and unique [47.7]. Thus the efficiencies achieved through mass production are not easily achieved in construction.

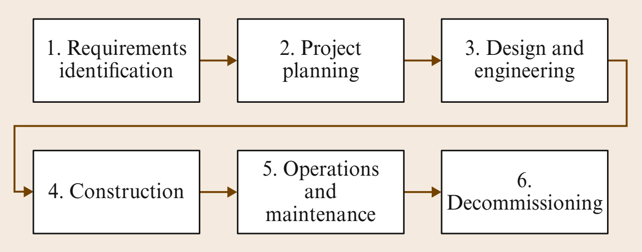


Fig. 47.1 Phases of a typical construction project

Other often attributed reasons for the construction industry's technological lag are the industry's fragmentation and aversion to the risks associated with the introduction of new technologies [47.7, 8]. In addition, unlike their manufacturing counterparts, construction sites are for the most part unstructured, cluttered, and congested, making them difficult environments for robots to operate in. Furthermore, human workers are also present in large numbers on a construction project, making safety a paramount concern.

Types of Construction

Construction projects are usually classified as residential, commercial, industrial, or civil. Residential construction generally involves single-family homes or large apartment buildings; commercial focuses on building structures such as office and retail space, warehouses, and so on; industrial is involved in building factories, power plants, and other similar structures; and civil construction focuses on public infrastructure such as highways, bridges, tunnels, and dams.

In the USA (as of 2006), residential construction accounted for a little over half of the total construction value put in place [47.2]. Among nonresidential construction activities, commercial, civil, and industrial projects accounted for approximately 26%, 17%, and 4%, respectively, according to census data for the 4 years between 2002 and 2005 [47.2]. According to the same census data, approximately 78% of all construction activity in the USA is undertaken by private firms.

In the EU (as of 2005), civil construction accounted for 20% of the total construction put in place, nonresidential construction for 31%, renovation and maintenance for 23%, and new residential building for 26% [47.9].

The Typical Construction Project

A construction project typically goes through six major phases, as shown in Fig. 47.1. Some projects may go through different variations of the sequence shown, but most projects include planning, design, construction, and operation phases [47.4,7]. Phase 1 begins when a need for a project arises and the requirements are identified. Phase 2 involves developing alternative project plans that could meet the identified needs and evaluating the technological and economic feasibility of each alternative. Phase 3 develops detailed engineering designs and specifications for the plan selected in phase 2. The construction of the facility from ground-breaking through to final inspection takes place in phase 4 of the project. The facility is occupied and commences operation in phase 5 and continues operating until it is time to shut down and dismantle the facility once it becomes obsolete (phase 6).

The actual physical work (building, operating, maintaining, and dismantling) on a construction project takes place in the last three phases. Although these are the only phases in which machines are used, construction automation can also take place during the other phases of a project, as described in Sect. 47.1.2.

During the various phases of a construction project, several stakeholders may be involved at any time. The major stakeholders include the following: the *owner* and *operator*, whose needs initiated the project; the *architect* and *engineer*, who have the task of translating the owner's needs into an aesthetically pleasing and structurally sound design; and the *general contractor*, whose task is to translate the design into a physical structure. In addition several other stakeholders may be involved either independently from the above stakeholders or as part of their organizations; for example, the constructor may employ a project manager, a construction manager, a site superintendent, and others, and he/she will typically subcontract major activities such as excavation and concrete pouring. The subcontractors and sub-stakeholders are often the ones who use a new technology and can either *make or break* its implementation.

Although the builder is the most likely user of robots on a construction project, the actual work on site is often conducted by subcontractors who often are reluctant or financially unable to use advanced technologies which have not been entirely adopted by industry. A constructor's goal is often to meet the owner's requirements by the most efficient *and* least risky methods possible. Hence, traditional construction methods that have stood the test of time are preferred. Nevertheless, it has often been anecdotally reported that the owner has *the power* to require the use of certain technologies on a construction project, since that shifts part of the risk and cost associated with the use of the technology to the owner. This phenomenon may be partially responsible for the widespread penetration of laser scanning technology into the construction industry that is currently taking place [47.10].

47.1.2 Automation in Construction

Construction automation describes the field of research and development focused on automating construction processes, and the use of robots is but one aspect of that field. In short, construction automation deals with applying the principles of industrial automation to the construction sector, whether in building construction, civil engineering (roadways, dams, bridges, etc.), or in prefabrication of construction components [47.11]. This can be viewed as an extension to research in field service robots generally designed to replace or assist humans in a specific construction-related task or function.

From a historical perspective, research in construction robotics and automation started in the 1980s with the introduction of single-purpose robots (principally remotely controlled, or teleoperated, machines). The Japanese led this effort, driven primarily out of concern for societal demographics, which showed a significant future shortfall in personnel available for the construction labor pool [47.12]. In the US the principal related work involved developing remote control or teleoperated machinery for hazardous work that required modified construction equipment. Example applications include robots developed for rapid runway repair and unexploded ordinance removal. In the EU, research was focused on the development of large-size masonry (brick laying, assembly) robots for residential and industrial building construction.

During the next decade, as research on task-specific construction robots continued, large Japanese construction firms introduced on-site *factories* for high-rise construction. These construction systems included just-in-time delivery of components, automated part tracking and material handling, robotic connection and assembly, and centralized control in an enclosed or semi-enclosed environment. It is reported that the systems enable better working conditions (weather invariant) and reduced project completion time [47.13]. Other benefits include improved productivity and quality, though overall construction costs are not necessarily lower [47.14].

Advanced concepts in integrated residential construction automation were developed as part of the EU FutureHome project. In this construction concept, each structure consists of several high-quality, prefabricated three-dimensional (3-D) modules and two-dimensional

(2-D) panels which are assembled *production-style* on site [47.15]. An analogue of this approach for automated residential construction has been commercialized in Japan [47.16].

New methods for collecting, processing, analyzing, and communicating construction information are a significant area of construction automation research [47.17]. This research includes data interoperability and exchange through the design, construction, operations, maintenance, and decommission phases of a capital project [47.18]; advanced sensors for assessing the status of the construction process [47.19–21]; visualization systems for planning construction events, verifying constructability, and maintaining site situational awareness [47.22–24]; and information models which extend traditional computer-aided design (CAD) modeling to combine both the physical (geometric) and functional characteristics of building components [47.25].

Finally, three notable, large-scale, ongoing EU projects are attempting to integrate construction automation into the way construction projects are executed: the ManuBuild (open building manufacturing) project deals with, among other things, the development of mobile field factories, including robots, for on-site modular construction [47.26]; the I3CON (industrialized, integrated, intelligent, construction) project deals with the indoor automation and robotization of buildings [47.27]; and the Tunconstruct project deals with the robotization of inspection and maintenance operations in tunnels [47.28].

47.1.3 Robotics in Construction

Construction robotics is an advanced form of mechanization (automation) in which an endeavor is made to automate some industrially important operation and thereby reduce the cost of this operation by either removing a human operator *from the control loop*, or enhance operational efficiency through machine control systems. Due to the nature of construction work, most robots which have been developed for the construction industry are either mobile or relocatable systems. Some platforms, such as floor-finishing robots and machine-controlled earthmovers require mobility as a specific function of the work process to be performed. Others, such as wall and ceiling panel manipulators, require some level of mobility to extend their operating workspace.

Robot terminology can vary depending upon the research discipline. For this chapter three general categories of construction robots are introduced. The first class is *teleoperated systems*, which for simplicity includes *remote control systems*. The general distinction between the two terms is whether or not the equipment must be operated in line of sight from the human controller [47.29]. The second category, *programmable construction machines*, includes most construction equipment that is outfitted with sensors and mechanisms to augment operation by an onboard human operator. The final category, *intelligent systems*, relates to unmanned construction robots which operate either in a semi- or fully autonomous mode. In Sect. 47.3 this classification will be expanded to include examples based on various generic activities, materials handled (operand types), levels of onboard intelligence, levels of commercialization, and levels of system integration and computer integration.

Teleoperated Systems in Construction

In established engineering terminology, the term *teleoperation* refers to the remote control of machines and systems. In teleoperation (loosely referred to as telerobotics) the control of the machine is accomplished by the use of remote control means such an umbilical cord or wireless control. Teleoperation ideas and methods are used extensively in the space and nuclear industries (Chaps. 45 and 48, respectively).

In telerobotics, the machine does not operate autonomously but is under the control of a human. Data sensing and interpretation and cognitive activities such as task planning are done by the operator.

Recently, many telerobotic devices have appeared in the construction and mining industries. These machines have evolved in response to industrial situations where there is danger to the operator and where remote-controlled machinery is necessary (e.g., teleoperated small compactors). Situations of this kind occur in the construction, demolition, and mining industries and in other hazardous locations.

The technology for telerobotics in construction is well established, with a number of excellent examples of such activity available, for example, a sophisticated model-based supervisory-control-type distributed teleoperation system for the construction of a trench for a diversion dam in a lava field in Japan using a fleet of heavy earthmoving machines [47.30].

Programmable Construction Machines

A software-programmable construction machine is what most people would consider to be a robot. The operator of this type of machine is able to vary the task to be accomplished within certain constraints either by choosing from a preprogrammed menu of functions or by *teaching* the machine a new function. Variations in the task to be accomplished could be as simple as slight changes in the driving speed based on the current load for an automated forklift, or as complex as a change from being able to pick and place steel beams and columns using an autonomous crane to being able to deliver concrete autonomously using the same crane.

Generally, software-programmable construction machines are identical to traditional construction machines (such as an excavator), but have been modified to be controllable through a computer [similar to the way in which traditional manufacturing machines – such as mills and lathes – evolved into computer numerically controlled (CNC) machines].

Software-programmable construction machines can make use of an electronic representation of a portion of the construction site where their work is to be conducted in order to control all or part of the machine's operation. A commercialized example is *stakeless grading*, where data from a 3-D model is used in combination with global positioning systems (GPS) and/or laser measurement systems to automate the blade control for bulldozers and motor-graders.

Intelligent Systems in Construction

As opposed to a teleoperated or a software-programmable construction machine a fully autonomous construction robot is expected to accomplish its task, within a defined scope, without human intervention. A semiautonomous construction robot would be expected to accomplish its task with some level of planning interaction conducted with a human supervisor [47.29]. In each case the construction robot is expected to adapt to its sensed environment, formulate plans for the execution of its task, and replan as necessary (with possibly some human assistance in the semiautonomous mode). The intelligent construction robot should also be able to determine when its tasking is not executable and request assistance.

Example research in intelligent construction systems includes autonomous excavation [47.31, 32] and autonomous crane operations [47.24, 33–35].

47.1.4 Sensing Systems in Construction

Field measurements are an integral part of the construction process. The *tape measure* and the *transit* have been used in construction for decades for measuring distances and angles, respectively. However, construction measurements are not limited to distances and angles, but can also include measurements of installed quantities, percentages of completion of activities, and so on. All of these measurements are necessary to be able to lay out the site where a facility is to be built, to measure the conformance of the as-built facility to the intended design, and to monitor safety, productivity, and progress.

Traditional Sensing Systems

In addition to the tape measure, transit, and level, all of which are still in use [47.36], more modern sensing systems are now considered commonplace (or traditional) at a construction site. These include total stations [or digital theodolites – a combination of a theodolite and an electronic distance measuring (EDM) device], GPS, and laser planes, levels, and plummets. Although GPS is commonplace in construction (and many other industries) and may be considered a traditional sensing system at this stage, it is and will continue to be a significant enabler for construction automation.

Advanced Sensing Systems

More advanced sensing systems are also beginning to have some impact in the construction industry. Some of these technologies are, and will become more so in the future, key enablers for the introduction of automation and robotics onto the construction job site by providing real-time situational awareness of site conditions. Some of these advanced sensing systems are described below.

Real-Time Positioning Systems. Traditional GPS relies on line of sight (LOS) to Earth-orbiting satellites and cannot currently track a moving object at much better than 20 cm unless ground-based stations are used. For applications where LOS to the GPS satellites is not available (such as indoors) or where higher real-time accuracy is required, two technologies currently exist: laser-based (also often referred to as indoor GPS) and ultra-wideband positioning systems. Indoor GPS (iGPS) relies on LOS to a series of laser transmitters (beacons) to measure and track the position of an optical receiver at up to 100 m away from the closest beacon [47.37]. Ultra-wideband (UWB) relies on LOS to a series of radio receivers to measure and track the position of a radio transmitter (working in the microwave frequency) at up to 200 m away from the closest receiver. Both technologies are similar to satellite-based GPS in that multiple objects can be tracked using the same infrastructure created by a few fixed beacons or receivers and that tracking can be quickly regained following a break in the LOS. (In the case of UWB, direct LOS is not always necessary since the UWB signals can travel through many common construction materials, albeit at the possible cost of degradation in the positioning accuracy.)

Laser-Based 3-D Imaging Systems. Laser-based three-dimensional (3-D) imaging systems use lasers to measure the range to points on objects within their field of view, as well as the bearing (angles) to those points within the instrument's coordinate frame. These systems usually output a *cloud* of points (or *point clouds*) with 3-D coordinates (usually X, Y, Z or angle, angle, range) associated with each point. In addition, many of these systems also output the intensity of the returned signal from each measured point on the objects as well as the red, green, and blue (RGB) color information from each point. Laser-based 3-D imaging systems are commonly also referred to by some of the following names: laser scanners, laser radar or laser detection and ranging (LADARs), and light detection and ranging (LIDARs).

The use of laser-based 3-D imaging systems is rapidly penetrating the construction industry due to its efficiency in capturing the existing conditions of a construction project (during or after construction) in great detail [47.10]. Gathering as-built conditions is essential for facility redesign, maintenance, repair, and upgrade and the ability to efficiently and accurately measure the condition of the existing facility and can have significant time and cost savings.

Ground-Penetrating Radar. Ground-penetrating radar (GPR) uses electromagnetic radiation at the microwave frequency (also known as *ultra-wideband*) range to measure reflections from objects buried underground or within structures (similar to traditional RADAR). In construction, this technology has been used to locate buried utilities before digging [47.38], to measure pavement layer thickness [47.39], to inspect concrete bridge decks [47.40], and to measure soil water content [47.41].

Structural Health Monitoring Systems. Structural health monitoring technology uses in situ, nondestructive sensors [e.g., strain gages, ultrasonic sensors, optical fibers, micro-electromechanical systems (MEMS) sensors] in order to detect structural damage or dangerous conditions [47.42]. These sensors are best deployed as a network of wireless sensors and can be used to monitor the state of a structure as it is being built, to monitor its health during normal operation, and to help determine structural integrity after an extreme event.

Equipment Health Monitoring Systems. Similar to structural health monitoring, these systems allow equipment operators to monitor the state of the machine (e.g., peak loads, tire pressures, engine temperature, hours in operation, crane tilt). The systems can also suggest when a machine needs maintenance and can even safely shutdown a machine should dangerous or undesirable conditions occur.

Concrete Maturity Meters. Concrete maturity meters use disposable sensors that are embedded in the concrete before it is poured in order to measure the internal temperature of the curing concrete and determine the developed strength [47.43]. Other systems use the dielectric properties of wet concrete to estimate the developed strength [47.44].

Radiofrequency Identification. Radiofrequency identification (RFID) is a relatively new addition to the construction sector. With the complete acceptance and adoption of RFID by some of the world's largest retailers (such as Walmart and Target) and by the US Department of Defense, this technology is evolving rapidly and the construction industry is poised to benefit from it.

The implementation of RFID technology involves the combination of RFID tags and tag interrogators. Each RFID tag has a unique identification number permanently stored on a microchip [usually in read-only memory (ROM)] embedded within the tag. Tags can be passive, semiactive (or semipassive), or active. An interrogator transmits a radio wave at a specific radiofrequency (RF) and waits for returned signals from tags that are within range. For passive tags, an onboard capacitor accumulates enough of the interrogator's RF energy (due to current induced in the tags antenna) to transmit the tag's unique identifier back. For active tags, an onboard battery powers the transmit function and can be used to maintain data stored in random-access (volatile) memory (RAM). In semiactive tags, an onboard battery is used to maintain data stored in RAM, but the transmit function still relies on the induced current to charge a capacitor.

Applications of RFID technology in construction to date have been in the research and development domain. Pilot projects have been conducted to test the effectiveness of RFID for tracking the delivery of construction components (e.g., pipe spools) to the construction site and to maintain an inventory of available parts and tools on site [47.45–48]. The application of RFID technology is likely to benefit the construction industry significantly in the short term (since projects are often plagued

47.2 Economic Aspects

47.2.1 Scope

In general, construction system designers are interested in the development of efficient production systems using available technology. Typically, such systems designers use new processes and technologies as they become available and as they prove to be economically viable. In relation to automation technology, such technology will not be introduced if only *islands of automation* are implemented with little overall system benefit [47.49].

47.2.2 Motivation

Apart from the pursuit of economic efficiency, construction robotics has technical features that have the potential to add value to the construction process and to product timeliness and quality, for example, there are work quality benefits such as in the quality and reliability of welding and inspection tasks. Furthermore, automated performance monitoring systems can give construction agencies hard-copy data for quality control and quality assurance purposes. The provision of historical compaction data in the construction of roads is a good case in point [47.50].

As a unique technical feature, construction robotics has the potential for reducing of occupation health and safety (OH&S) risks by removing workers from danger zones and high levels of noise or air pollution [47.51]. Construction can be a dangerous activity with a relatively large number of people being killed or injured annually (when compared to other industries).

Robotics has a major potential for allowing construction work to be undertaken in very cold or very hot weather and in areas subject to extreme radiant heat (such as building or bush fires or near blast furnaces) or nuclear radiation, for example, an early use of telerobotics was the remote control of concrete pumps in the encasement of the Chernobyl nuclear power plant in the Ukraine. Likewise, the remote control of underwater bulldozers and other types of underwater equipment is an obvious area for the technical attributes of construction robotics.

47.2.3 Barriers

Technical and Commercial Barriers

While technology researchers and developers may be interested in construction robots for their own sake, the typical purchaser of such systems is a contractor or construction agency who is predominantly interested in machinery systems as an instrument of purpose or as a *tool-of-the-trade*. For a particular application, robotic or automated systems or machines must compete with existing labor-intensive solutions and alternative technological solutions.

As a generalization in 2006, it is fair to say that currently available construction robotic solutions do not undercut traditional labor-based solutions except in special niche areas. This is in contrast to the widespread use of robotics in the manufacturing sector.

Some of the economic difficulties associated with the application of robotics in construction stem from the characteristics of the industry. Because it is primarily concerned with the production of large-scale custom-made capital goods that are specifically designed to fit a site, the construction industry is characterized by unique products and low production volumes and in situ development processes in open-air environments. Historically, the construction industry has proven substantially unsuited to the hard-automation methods that have been successfully developed in the large-volume repetitive applications in the manufacturing sector [47.52].

Using manufacturing industry terminology, construction may be categorized as a *jobbing-type* industry. Typically, the construction industry has very low levels of repetition and normally has *job lots of one*.

To increase the level of internal repetition, methods of product standardization have been introduced. Over the last 50 years, standardization and extensive experimentation with systems-building methods have occurred in the industrialized building sector (in places such as the old Union of Soviet Socialist Republics) and in attempts to produce manufactured homes and buildings. Such attempts have largely failed due to a lack of product and process flexibility and to market acceptance of the products [47.53].

Potentially, the emergence of robotics and flexible manufacturing methods will have a great impact on the construction industry since product and process variety can be accommodated much more easily than with hard-automation methods.

Because the construction industry is fully established and has its own methods and techniques, the likelihood is that it will robotize its own forms of equipment rather than simply move industrial robots from the factory to the site.

Sociological and Industrial Barriers

Apart from commercial barriers many people are concerned that there will be substantial industrial or worker resistance to the widespread introduction of on-site robotics. The possible reason for worker resistance is potential job losses through displacement of labor.

47.3 Applications

Applications of robots in construction span a wide and diverse range. While certain robots with limited intelligence are slowly finding their way onto construction sites around the world, others remain scaled-down prototypes under development at universities and research organizations.

Classifying the extent of construction robot applications using a single scheme would be a daunting task, especially since some robots are being developed for multiple applications. Classification could be by level of commercial success, type of task performed, industry sector, physical scale of device, degree of technical complexity, level of onboard intelligence, and so on. Classification could also be by type of actual construction activity involved.

From a purely physical-world and practical point of view, construction may be viewed as being comprised of a finite number of elementary processes [47.55–58], which may be summarized by the following list [47.8]:

- Attaching
- Building
- Coating
- Concreting
- Connecting
- Covering
- Cutting
- Digging
- Finishing
- Inlaying
- Inspecting
- Jointing
- Measuring
- Placing
- Planning
- Positioning
- Spraying
- Spreading

Most of these processes can also be grouped into three predominant types of functional operators as follows:

1. materials handling (by bulk and unit load)
2. materials shaping (cutting, breaking, compacting, and machining)
3. structural joining

These functional operators are typically each applied to multiple operands. Common operands in building and civil engineering are steel and other metals, concrete, timber, earth and rock, masonry, plastic and glass, cement, aggregate, epoxy resin, bitumen, and other bulk and formed materials.

In the interest of brevity, the applications presented in Tables 47.1–47.10 have been loosely organized into two categories: (1) construction and (2) maintenance and decommissioning. Within these categories, robots are organized by the type of construction activity that each performs, but not necessarily following any of the classification schemes presented above. The list of applications is not comprehensive, but is meant to be a fairly representative sample of the types of robots currently being used in, or developed for, the global construction industry. (Although certain commercial construction equipment are included in this section, the inclusion of such information should in no way be construed as indicating that such products are endorsed by the National Institute of Standards and Technology (NIST) or are recommended by NIST or that they are necessarily the best equipment for the purposes described.)

47.3.1 Construction

Table 47.1 Materials handling **(a)** Six degree of freedom robotic crane [47.54]

Table 47.1 **(b)** Concrete panel installation robot (courtesy Fujita Research) **(c)** Large scale pipe manipulator **(d)** Large manipulator system (courtesy Shimizu Corp.)

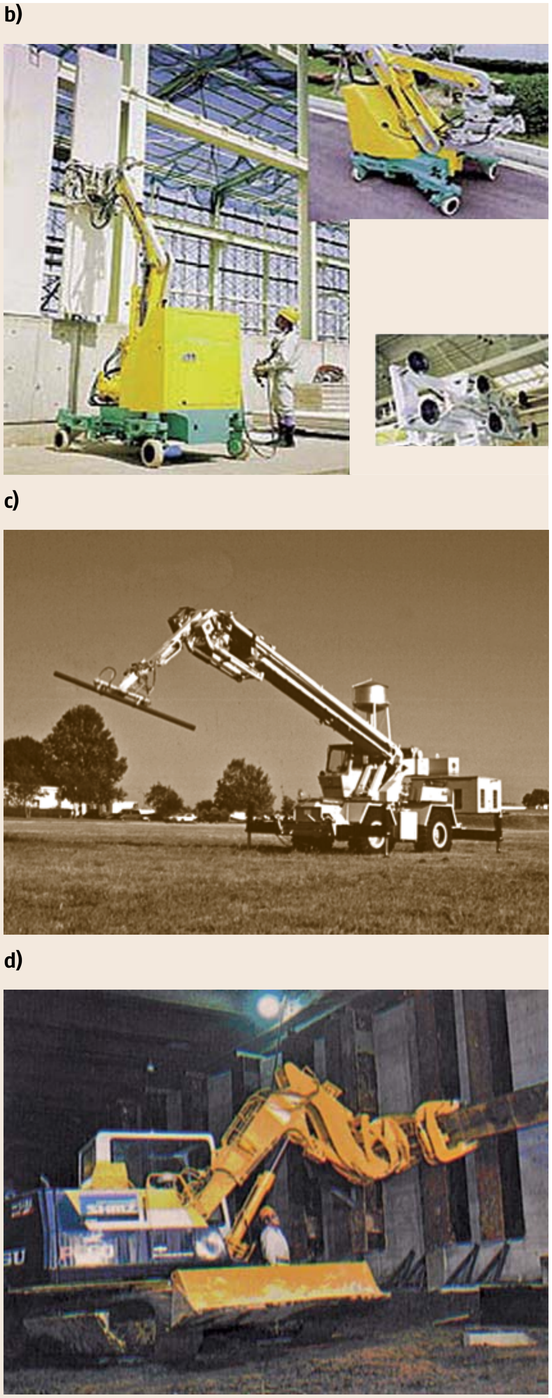


Table 47.2 Earthmoving **(a)** Teleoperated excavation system (courtesy Fujita Research) **(b)** Computer assisted road compacting system [47.59] **(c)** Automated grading system (courtesy Caterpillar, Inc.)

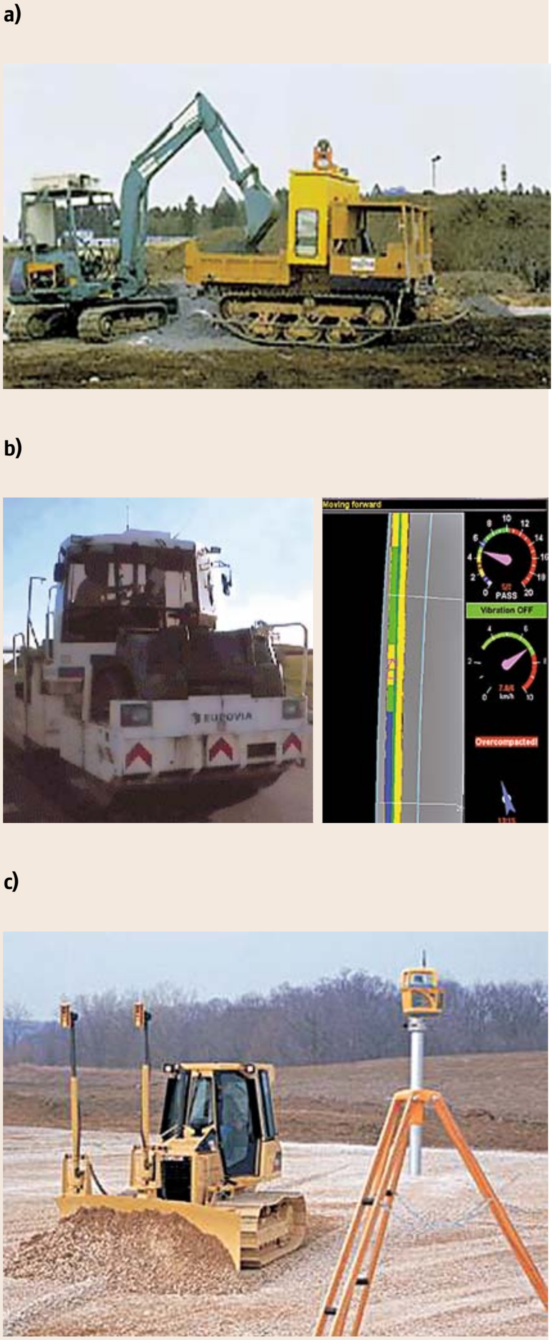


Table 47.2 **(d)** Automated drag line control system [47.60] **(e)** Autonomous excavator robot [47.61] **(f)** Autonomous off-road dump truck [47.62]

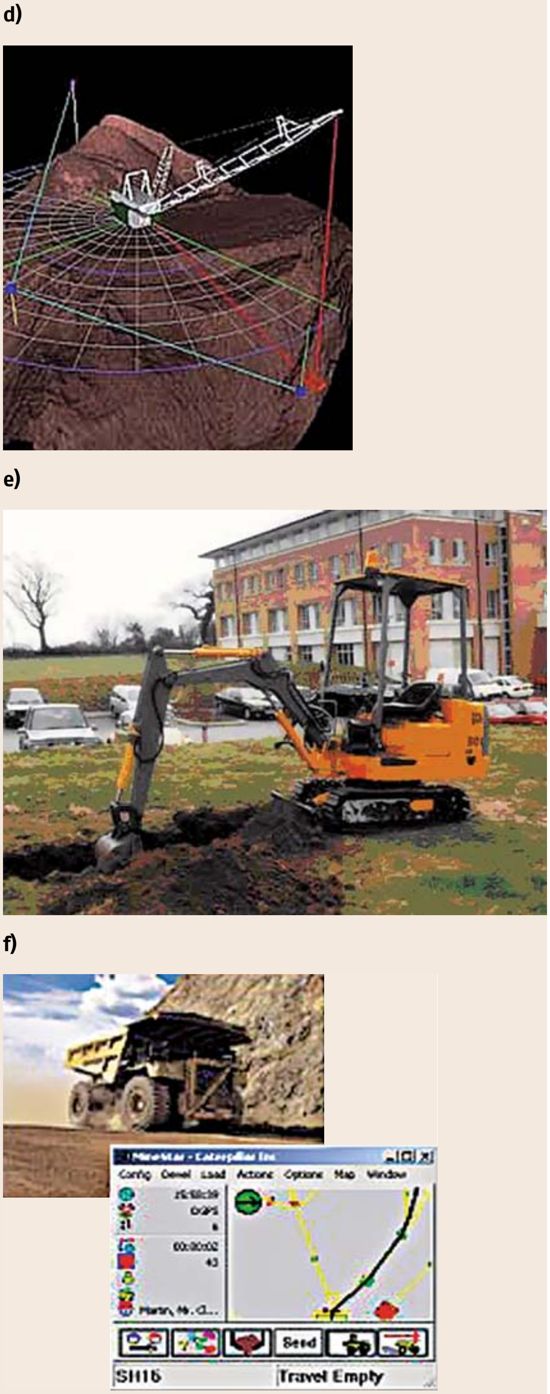


Table 47.3 Concrete placement and finishing **(a)** Concrete surface finishing robot [47.63, 64] **(b)** Programmable, articulated-boom machine for the pumped delivery of fresh concrete [47.65] **(c)** Auto-leveling concrete screed machine (courtesy Somero Enterprises, Inc.)

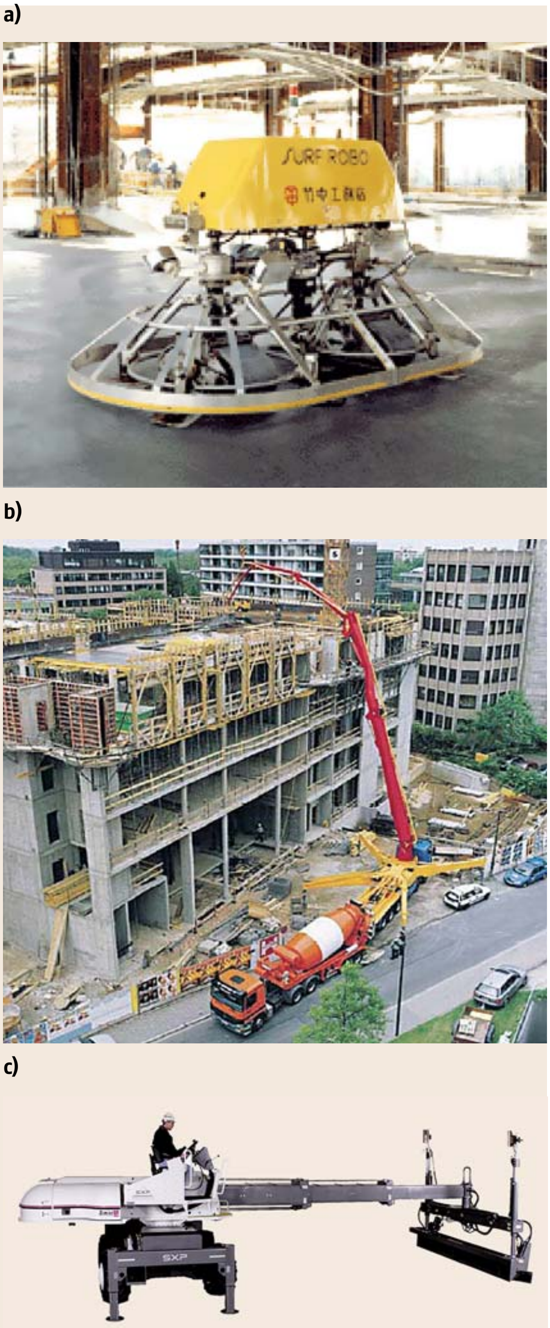


Table 47.3 **(d)** Concrete slipform road paving machine (courtesy GOMACO Corp.) **(e)** Teleoperated concrete spraying robot (courtesy MEYCO Equipment) **(f)** Concrete block laying robot [47.66]

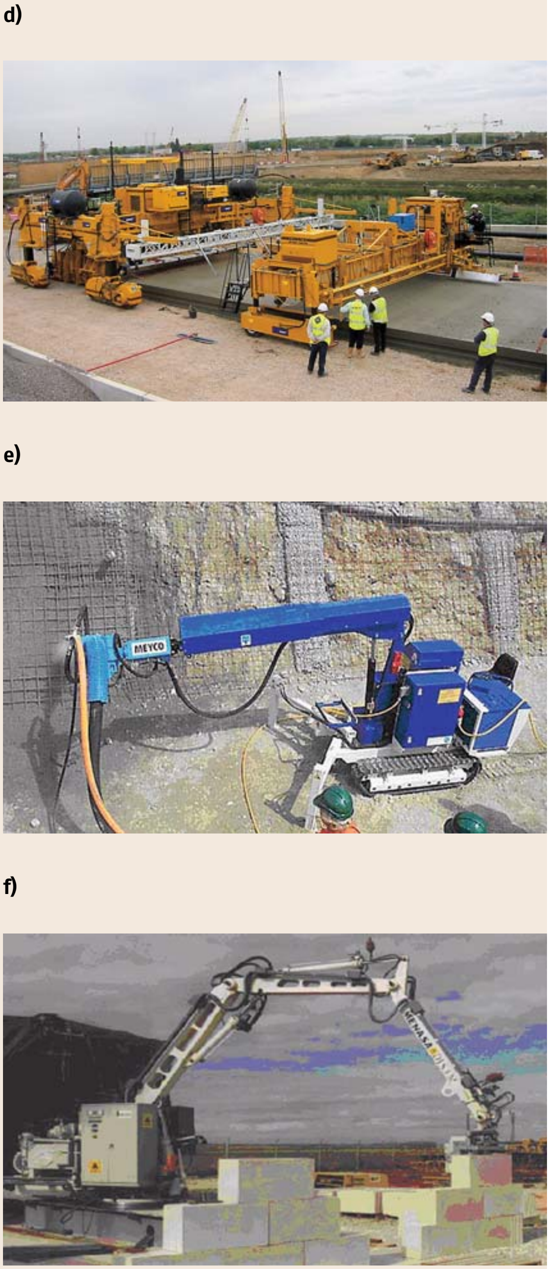


Table 47.4 Hard and soft rock tunneling Automated rock drilling robot (courtesy Bever Control AS)

Table 47.5 Precast concrete production **(a)** Automated concrete pipe manufacturing machines (courtesy Hawkeye Group USA)

Table 47.5 **(b)** Precast concrete handling robot (courtesy Halo, Inc.)

b)

Table 47.6a,b Structural steelwork production and erection **(a)** Autonomous steel column welding robot [47.11] **(b)** Autonomous structural steel pick-and-place robot [47.67]

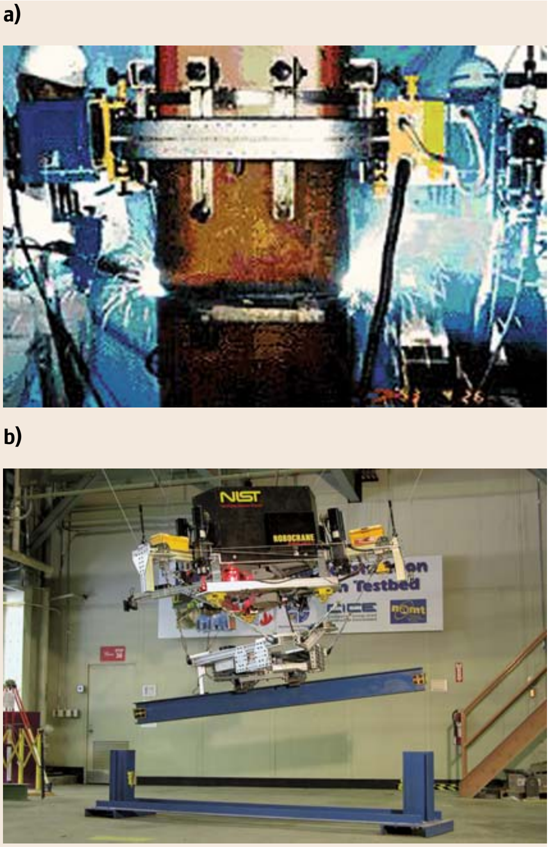


Table 47.6 **(c)** Teleoperated rebar placing robot [47.11]

c)

Table 47.7a,b Whole building production systems **(a)** Onsite factory building construction [47.68] **(b)** Autonomous manufactured home construction robot [47.15]

47.3.2 Maintenance and Decommissioning

Table 47.8 Road maintenance **(a)** Teleoperated pothole patching robot (courtesy Leeboy)

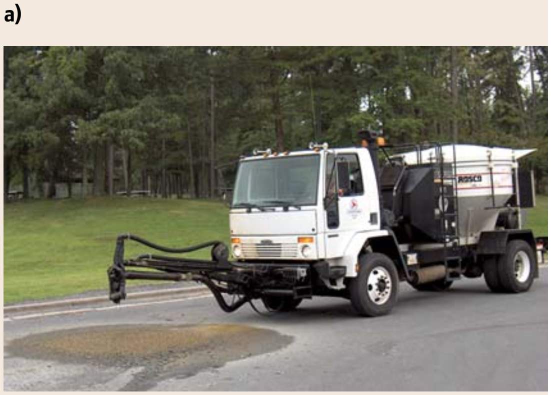


Table 47.8 Road maintenance **(b)** Semi-autonomous road crack sealing robot [47.69]

Table 47.8 Road maintenance **(c)** Semi-autonomous road crack sealing robot [47.70]

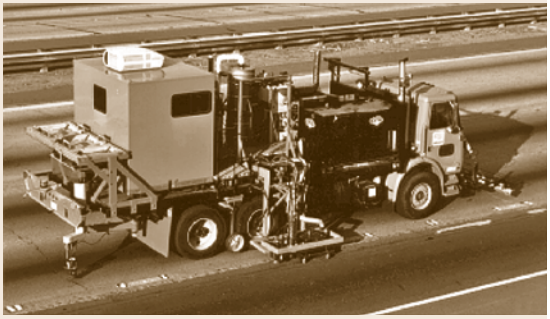


Table 47.9 Inspection **(a)** Teleoperated climbing inspection robots [47.71]

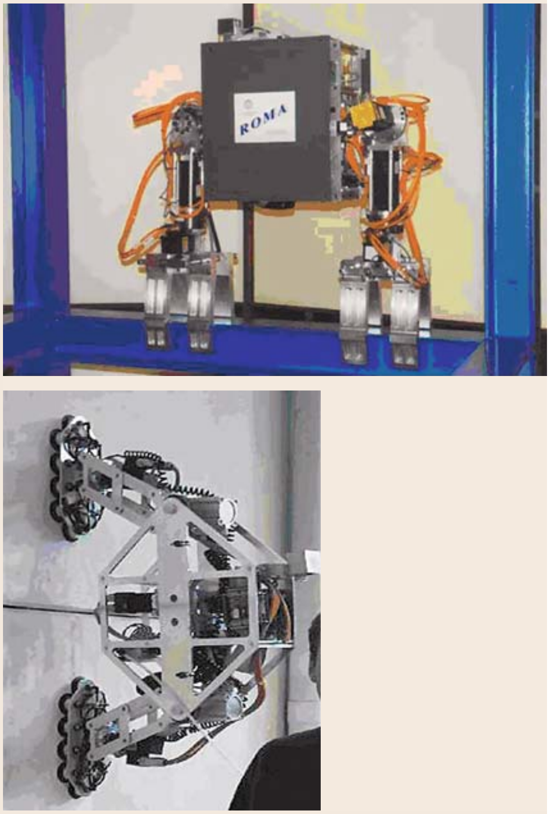
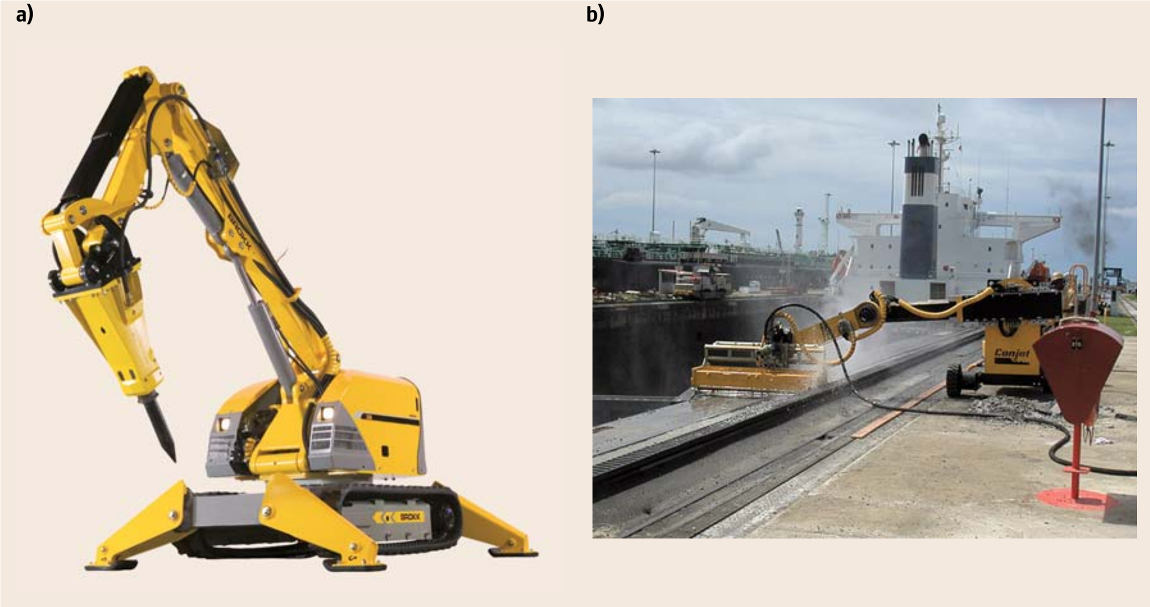


Table 47.9 Inspection **(b)** Teleoperated bridge maintenance and inspection robot [47.72]

Table 47.10a,b Demolition **(a)** Teleoperated demolition robot (courtesy Brokk AB) **(b)** Water-jet demolition robot (courtesy Conjet AB)



47.4 Currently Unsolved Technical Problems

47.4.1 Interoperability

A recent study found that the US construction industry does not realize approximately 15 billion US dollars per year in potential savings due to inadequate interoperability related to information exchange and management practices [47.73]. Although the lack of interoperability between the various information systems used in construction is a significant source of inefficiency for the industry, it is also a roadblock to the use of automated systems in construction. Automated systems need electronic information on past, current, and/or projected future states of a construction project to function efficiently.

For example, in order for a robotic crane to pick a steel beam from the site and deliver it to its target location, the robot must be able to know that the steel beam has been delivered to the site, as well as its current position and orientation. While information on the current inventory of parts on a site may be available on paper, it is rarely available electronically unless someone enters it manually into some computer system, which in turn may not be compatible with other systems used in that project. In many of the examples of automated construction technologies presented in this chapter, custom electronic databases and/or data formats have to be devised to demonstrate the robot's operation. In some cases, the electronic information had to be entered manually from paper into a computer for the robot to work correctly.

In addition to information exchange and management, many of the measurement instruments and sensors used in construction are not interoperable. This problem is not limited to the construction sector but is a relatively large problem in many robotic applications where different types of sensors are used. Several efforts are underway to make sensors interoperable [47.74] and construction equipment in general [47.75], but the issues have yet to be resolved.

47.4.2 Structural Connection Systems

Traditionally, structural member connections in construction have been designed for human installation.

Whether using bolted, welded, or other types of connections, manual labor is usually involved in guiding the mating parts together and in establishing the connection.

For example, in structural steel erection, workers perched on the structure typically guide a crane operator through visual or auditory cues in order to maneuver a steel beam (or column) into place. The workers must then physically manipulate the beam in order to align corresponding surfaces for bolting or welding. Once the correct beam pose has been achieved, it must be maintained while the workers temporarily fasten the beam to the structure. The workers then release the beam from the crane and permanently fasten the beam to the structure at a later stage.

For automated (or robotic) construction to work, new connections that are more amenable to automation must be designed. These connections need not mimic traditional, human-installed connections, but should be optimized for use with robots instead. For example, the Lehigh University Advanced Technology for Large Structural Systems (ATLSS) Center designed a gravity-load-only shear steel connector [47.76] back in the early 1990s that is more suitable for automated construction (Fig. 47.2). This type of male–female connector for automatic assembly of building modules allows, together with an adequate control strategy, small tolerances, which permit assembly by automatic cranes [47.77]. An example of a nonstructural connector that is more amenable to automation is the piping and electrical connector developed for the FutureHome project, shown in Fig. 47.3 [47.15].

Although automated welding has been applied in some limited form in construction, it is generally used to replace manual welding without changing the design of the parts being welded. In other words, no significant change in the way in which construction components are designed has occurred as a result of automated welding. Moreover, apart from a few examples of automated welding applied at the construction site, most of the other limited applications are done at the component fabrication facility.

Fig. 47.2 A drop-in, shear-load-only, steel connection

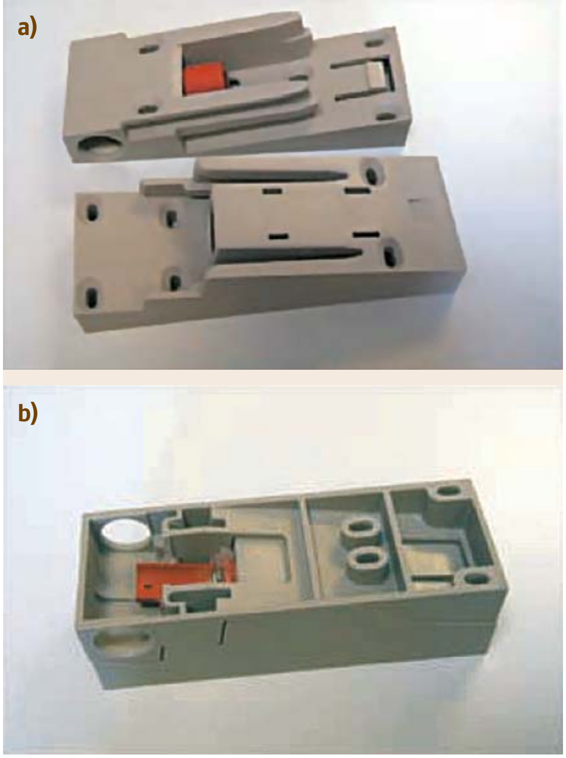


Fig. 47.3a,b A piping and electrical drop-in connector shown **(a)** disassembled and **(b)** assembled

47.4.3 Tolerances

Specifications for tolerances in the construction sector exist for most types of construction, however, they are not always achieved in practice [47.78]. For example, it has been stated that one of the biggest sources of problems in structural steel erection in the US is that fabricated pieces are often out of tolerance, and that this is only discovered during installation at the construction site [47.79]. However, since the finished facility must meet the design tolerances before it is accepted, this shifts the burden to workers and supervisors during construction. The workers are expected to handle problems as they come up rather than expect all fabricated construction components to be within tolerance. Since most construction projects are under tight schedules, it is often preferable to fix these kinds of problems on site rather than wait for replacement components to be fabricated and delivered.

However, tolerance problems are not all due to fabrication errors. Installation problems are also responsible for out-of-tolerance problems, for example, anchor rod installation has been an area of concern for structural steel erection. (Anchor rods (or bolts) are the connection interface between the concrete foundation and the structural steel columns. The rods are usually installed by the concrete foundation crew before the concrete is dry.) The situation of anchor rod patterns that do not match the hole patterns in a mating column is an identified problem in construction [47.20, 80].

Given the relatively loose achievable tolerances in construction, the application of robotics in construction faces an uphill battle. This, in addition to the unstructured nature of the construction site environment, requires that robots either be highly intelligent in order to correctly interpret and react to their surroundings or to be human assisted. However, site structure and tolerances are expected to improve as pressures to reduce costs and improve productivity continue to rise. Improvements in site organization and construction tolerances have already been proved to be achievable in a few cases, as has been demonstrated in Japan [47.53]. However, the economic case for these demonstration projects has yet to be made.

47.4.4 Power and Communications in the Field

Unlike manufacturing environments, in which specially designed factories are outfitted with the necessary power and communications installations, a construction project often begins before such resources have been installed at the site. Therefore, robots with large power requirements that need to communicate with supervisory systems located off site would be challenging to implement without significant added cost.

Although communications technologies have advanced significantly in the last few decades, it is still considered difficult to maintain a reliable local-area network at a construction site and to connect that network to the Internet. The use of cellular telephones with a press-to-talk (the digital version of the traditional two-way radio communication method) feature has largely replaced the traditional two-way radios that also revolutionized on-site construction communications. However, in order for construction sites to become more automated, reliable interference-free high-bandwidth networks must be able to carry data transmission between sensors, machines, and supervisory systems.

47.5 Future Directions

As previously discussed, developing new methods for collecting, processing, analyzing, and communicating construction information is a significant area of construction automation research, and will dominate near-term efforts. As this construction information becomes more readily accessible, automation of processes can be enabled directly from the combination of design information and current site status that is accurately captured and shared. Resource tracking will become ubiquitous and just-in-time delivery of needed materials and equipment will happen throughout the site.

Advances in mobility (humanoid robotics, smart cars, legged locomotion, etc.) will enable ever more automated material handling on the job site. These advances will require better control systems for the construction robots that can provide high payload and good positioning accuracy. The increased use of robots at the construction site will also drive research into safety systems for construction robots working around human workers and other machines.

Perhaps most important, more extensive automatic design systems will enable more prefabrication of building components and new methods of assembling those components on site, which in turn will provide the promise of faster, better, and cheaper construction robotics first envisioned in the 1980s.

47.6 Conclusions and Further Reading

The application of robotics to construction has yet to catch up with other industries such as automobile manufacturing. Construction presents a unique challenge for robotic applications. The construction environment is cluttered, unstructured, and teaming with human workers. In addition, construction processes are usually labor intensive and have to accommodate wide margins of error in the constructed facility. The application of robotics in construction to date has been limited to commercial teleoperated and programmable machines. Autonomous or semiautonomous machines are currently mostly limited to research projects within various nonconstruction organizations. With the increase in competition throughout the global construction market, construction companies are on the lookout for ways to improve productivity, quality, and safety. The use of automation and robotics is one answer that the industry is slowly turning toward. However, before these potential solutions can be successfully applied, much work is needed to improve construction tolerances, develop standards, and achieve real-time site status monitoring.

The International Association for Automation and Robotics in Construction holds an annual conference (the International Symposium on Automation and Robotics in Construction) at which researchers can present the latest developments in the field. The proceedings from this conference hold a wealth of information on the state of the art of the field and are accessible to the general public through IAARC's website (www.iaarc.org).

There are several journals that publish articles on various aspects of automation in construction. Most notable of these are *Automation in Construction*, *Computer-Aided Civil and Infrastructure Engineering*, the *Journal of Computing in Civil Engineering*, and the *Journal of Construction Engineering and Management*. In addition, some journals publish special editions on robotics in construction. Some examples are *Autonomous Robots* and the *Journal of Advanced Robotic Systems*.

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