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# ROBOTICS IN THE CONSTRUCTION INDUSTRY

BY

JAMES R. JACKSON



A REPORT PRESENTED TO THE GRADUATE COMMITTEE
OF THE DEPARTMENT OF CIVIL ENGINEERING IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING



UNIVERSITY OF FLORIDA

SUMMER 1990

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N00123-89-G-0549
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This paper is dedicated to my wife, Sonja, whose patience and understanding during the preparation of this paper is most appreciated. Without her love and support, this paper would have been most difficult to write.

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## ABSTRACT

This paper will investigate and discuss the principles of robotics, including robot movements and components, and how these principles can be used in the construction industry. Actual robotic applications in the construction industry will be examined and discussed, as will potential uses and applications. In this context, emphasis will be placed on those robotic applications in building construction, with passing reference made to other forms of construction robots. The social impact and economic considerations of implementing robotics technology in the construction industry will be discussed.

It should be noted that most of the information concerning robots and robotics concerns applications in the manufacturing industries. This is of little concern, however, because these same principles may also be applied to the construction industry.

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# CHAPTER ONE
# INTRODUCTION

## 1.1 INTRODUCTION

Robotics have been in use in the manufacturing industry for approximately 25 years. In fact, the auto industry serves as an excellent example of the uses and successes of robotics. Automobile assembly lines now include robotic welders, painters, and material handlers. Using robotics, the auto industry has enjoyed an increase in production and quality.

Much has been written regarding the use of robots and robotics in the manufacturing industry. In fact, many of the references for this paper deal exclusively with robots used in manufacturing. It should be noted that, although the types of industries and types of work may differ, the principles of robotics remain unchanged between industrial applications. In other words, the principles of robotics as applied to the manufacturing industry are the same as those for the construction industry. What does change is the end use of the robot, incorporating various advances in robotic technology (such as vision sensors, mobility, etc.) to accommodate the specific use and requirements for the robot.

The construction industry is the largest industry in the United States, employing approximately 5.5 million workers (approximately 6 percent of the total non-agricultural workforce) and accounting for approximately 8 percent of the Gross National Product (1-196). Indeed, construction accounts for approximately $400 billion annually in this country.

As evidenced by Table 1, the construction industry accounts for virtually none of the robotic investment or application in the United States. If the principles and technology of robotics are the same for all industrial uses, why then has the construction industry lagged behind in the implementation of robots? The purpose of this paper is to discuss the abilities and limitations of robotics, how these abilities and limitations could be advantageous in the construction industry, the current state of the art of robotics in the construction industry, the social and economic considerations of robotics, and future prospects for robotics in the construction industry.

| | 1985 | 1990 | 1995 |
|---|---|---|---|
| Agriculture | 1 | 1 | 1 |
| Mining and extractive | 1 | 2 | 2 |
| Construction | 0 | 1 | 1 |
| Electricity generation | 1 | 1 | 1 |
| Consumer non-durables | 2 | 5 | 5 |
| Non-metal primary commodities | 2 | 4 | 5 |
| Primary metals | 3 | 4 | 5 |
| Non-metal fabricated commodities | 5 | 6 | 6 |
| Fabricated metal products | 10 | 8 | 8 |
| Machinery | 8 | 10 | 11 |
| Electronics/precision equipment | 8 | 10 | 16 |
| Automotive | 51 | 38 | 26 |
| Aerospace | 6 | 6 | 8 |
| Other transport equipment | 2 | 3 | 4 |
| | 100% | 100%* | 100%* |

*Does not total 100% to rounding

Table 1 - Distribution of Robot Sales in the United States

Source: Ref. #1 - Robotics In Service

# CHAPTER TWO
# ROBOTICS: A GENERAL OVERVIEW

## 2.1 DEFINITIONS

### 2.1.1 Robotics

"Robotics is the science of designing, building, and applying robots. Robotics [is] a solid discipline of study that incorporates the background, knowledge, and creativity of mechanical, electrical, computer, industrial, and manufacturing engineering." (3-1) Scientists and engineers in several countries, most notably Japan, United States, and West Germany, are very active in researching and developing robotics technology. Tremendous progress in this area has been achieved in the past two decades. The advances in robotic technology are applied to various aspects of civilization and industry, with the manufacturing industries being the principal beneficiary.

### 2.1.2 Robot

In 1979, the Robotics Industries Association defined a robot as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks." (3-2) This definition serves as the international standard for all industries and professional societies. Breaking this definition down, the following key words and phrases are noted.

#### 2.1.2.1 Reprogrammable

A robot must be capable of being "fed" new or updated instructions. In general, robots are computer controlled; the computer uses a program for maneuvering and controlling the robot while performing its assigned task or operation. Reprogrammability allows the robot to perform an unlimited number of tasks or operations within the physical and mechanical capabilities of the robot itself.

#### 2.1.2.2 Multifunctional

A robot must be capable of performing more than one task, making the robot a versatile tool. This is usually accomplished through reprogramming and the attachment of different end effectors.

#### 2.1.2.3 Manipulator

This is the mechanism for moving objects in the performance of assigned tasks (programmed instructions).

#### 2.1.2.4 Various programmed motions

This characterizes the robot as a dynamic entity, with continuous productive activity.

## 2.2 BASIC ROBOT MOVEMENTS

In a three-dimensional world, a robot must be able to reach any point within its physical work area. Such points are described by coordinates, which can be easily defined and programmed into the robot's controller. In general, robots are classified into categories based upon the type and/or nature of movement their manipulator arm is capable of performing in reaching a predesignated point in space. This movement, in turn, defines the robot's work envelope, or the volume (expressed as a work area) within which the robot is capable of reaching. For many years, robots were classified into four categories: cartesian, cylindrical, spherical, and anthropomorphic. The first three categories describe robotic movement in accordance with established coordinate systems, while the last indicates that family of "jointed-arm" robots. The vast majority of all robots in existence today are classified in one of these four categories. Recent technology, however, has produced two additional categories: selective compliance assembly robot arm (SCARA) and spine robots.

### 2.2.1 Cartesian Robot

A cartesian robot moves its manipulator arm in the classical three dimensional coordinate system, which is called the cartesian or rectilinear coordinate system. This coordinate system consists of three mutually perpendicular axes (the x, y, and z axes), which allows the robot arm to move in/out, up/down, and forward/backward in linear motions. The advantage of this category is that any motion in one direction may be made independently of the other two. The work envelope for this type of a robot is a cube, away from the body of the robot. This type of robot has no capability to reach objects located overhead (above the robot's body) or below the robot's base. This type of robot is frequently employed in a gantry configuration. Figure 1 shows the axes of motion for this type of robot. Figure 2 illustrates the work envelope.

2.2.2 Cylindrical Robot

A cylindrical robot possesses the ability to rotate its manipulator about one axis, with linear movement along the other two axes. This rotational ability gives the robot a simple method for moving its manipulator in one plane. With

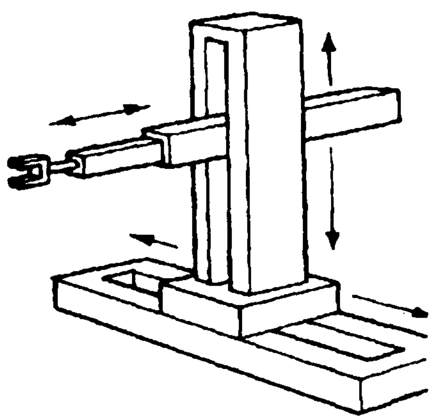


Figure 1 Cartesian Robot Arm Movements

Source: Ref. #4 - Fundamentals of Robotics: Theory and Applications.

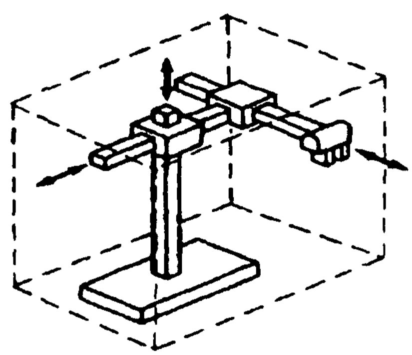


Figure 2 Cartesian Robot Work Envelope

Source: Ref. #5 - Robotic Technology: Principles and Practice.

this type of robot, rotation is usually around the base of the robot, with linear motion in the up/down and in/out directions. The work envelope for this type of robot is a cylinder with the central core removed (reserved for the robot's body). In simple terms, the work envelope for this type of robot may be visualized as a stack of donuts or lifesavers. This type of robot also has no capability for reaching points located overhead or below it's base. Figure 3 illustrates the motion capabilities. Figure 4 depicts the work envelope for a cylindrical robot.

### 2.2.3 Spherical Robot

A spherical robot possesses the capability to rotate its manipulator about two axes, with linear motion provided

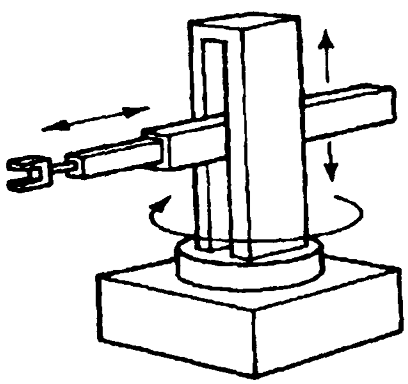


Figure 3 Cylindrical Robot Arm Movements

Source: Ref. #4 - Fundamentals of Robotics: Theory and Applications.

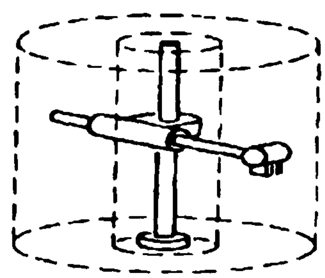


Figure 4 Cylindrical Robot Work Envelope

Source: Ref. #5 - Robotic Technology: Principles and Practices.

along the remaining axis. Rotation is usually provided about the base of the robot and in the up/down direction, with linear motion in the in/out direction. In general, the two rotational motions will point the robot manipulator at a programmed point in space, with the linear motion used to reach out to that point. The work envelope consists of a sphere with a pie or cone shaped segment removed (to accommodate the robot base). A spherical robot does have the capability to reach objects located overhead or below it's base. Figure 5 illustrates the motion capabilities. Figure 6 depicts the work envelope for a spherical robot.

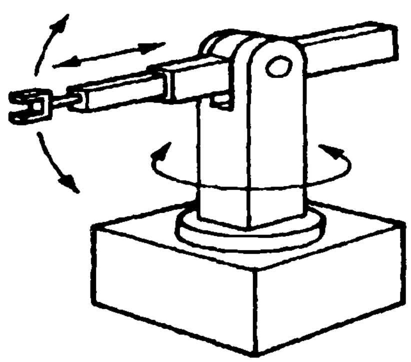


Figure 5 Spherical Robot Arm Movements

Source: Ref. #4 - Fundamentals of Robotics: Theory and Applications.

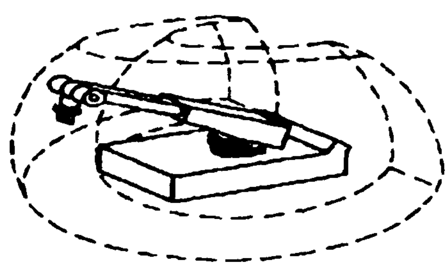


Figure 6 Spherical Robot Work Envelope

Source: Ref. #5 - Robotic Technology: Principles and Practice.

### 2.2.4 Anthropomorphic Robot

The anthropomorphic robot uses three rotational movements to reach any point in space. This type of robot is commonly referred to as the articulated or jointed-arm robot, possessing two rotational joints that physically resemble the human shoulder and elbow. This resemblance is purely physical, though, since the robot joints lack the flexibility and maneuverability of human joints. Each of these joints provides rotation about separate axes, with an additional rotation about the robot's base. The work envelope is a sphere, with scalloped interior limitations (due to physical limitations in the two joints). Flexibility in motion and operation are distinct advantages for this type of robot. Figure 7 illustrates the motion capabilities. Figure 8 depicts a side view of the work envelope for an anthropomorphic robot.

### 2.2.5 Selective Compliance Assembly Robot Arm (SCARA)

SCARA robots (refer to Figure 9) were developed and introduced by Professor Makino of Yamanashi University in 1988 (1-18). A SCARA robot possesses one or more rotational capabilities in one plane with limited movement capability in any other plane. In essence, this type of robot is adept at two-dimensional movement, with limited movement in the third dimension. In simple terms, this robot resembles a jukebox record changing arm, capable of transporting objects

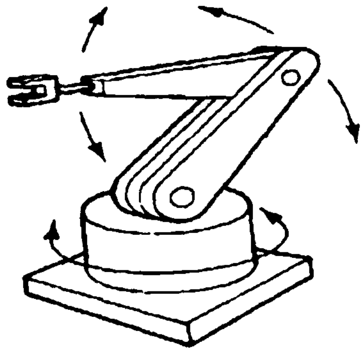


**Figure 7** Jointed-Arm Robot Arm Movements

Source: Ref. #4 - Fundamentals of Robotics: Theory and Applications.

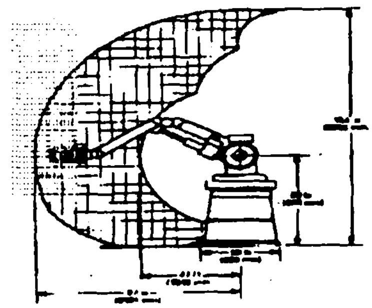


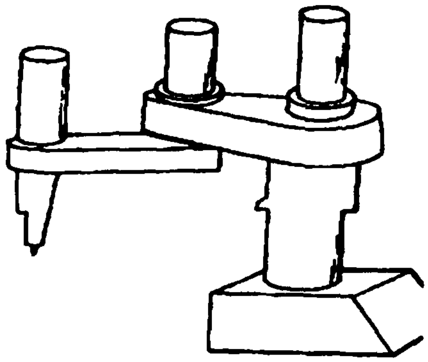
**Figure 8** Jointed-Arm Robot Work Envelope

Source: Ref. #3 - Robotics: A User Friendly Introduction.

from one point to another in the same horizontal plane. This type of robot was developed with an emphasis on assembly operations rather than manipulator movement; it is capable of handling relatively light payloads at fast speeds (1-18). The work envelope for a SCARA robot is essentially planar, with no depth or volume (refer to Figure 10).

### 2.2.6 Spine Robot

Another recent development in robotics was the spine robot (refer to Figure 11). This type of robot arm physically resembles the human spine. The spine robot consists of a series of disks connected by a number of external tendons (refer to the inset to Figure 11); each tendon, in turn, is connected to hydraulic or pneumatic actuators. The actuators change the length of the tendons,



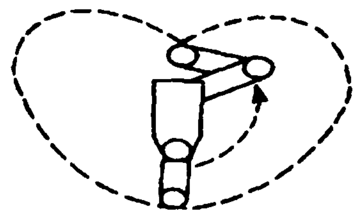


Figure 9 SCARA Robot

Source: Ref. #6 - Robotics: An Introduction.

Figure 10 SCARA Robot Work Envelope

Source: Ref. #6 - Robotics: An Introduction.

causing the robot arm to bend. It is readily apparent that flexibility is the biggest advantage for this type of robot, since it has the capability to reach around corners; in fact, the work envelope for this type of robot is limited only by the length and flexibility of the arm. The flexibility of the arm is limited by the number and construction of the disks, the number of tendons connecting the disks, and the number of actuator sections (allowing compound curvature of the arm). Disadvantages for this type of robot include slow movement (when compared to the other types of robots), limited repeatability (ability to "hit" the same point in space time after time without reprogramming or adjustment by the operator), and the ability to handle only light payloads (1-21).

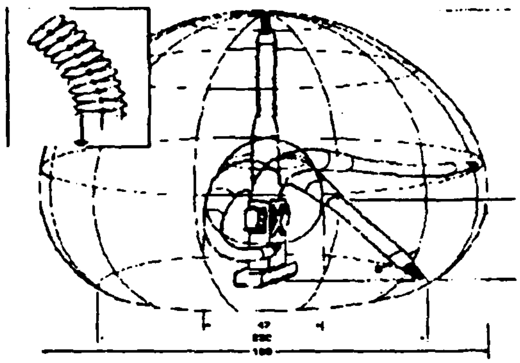


Figure 11 Spine Robot Arm Movements and Work Envelope

Source: Ref. #5 - Robotic Technology: Principles and Practice.

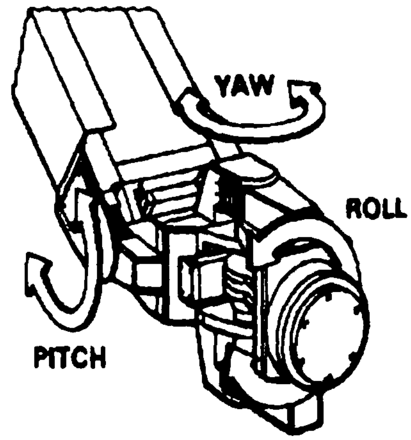



Figure 12 Robot Wrist

Source: Ref. #3 - Robotics: A User Friendly Introduction.

2.2.7 Wrist

Each of the above robot categories describes the movement of the robot arm. Movement of the robot arm ensures that the end of the arm will reach a specific point in space, but the arm itself has no capability of orienting the object being carried (end effector). The addition of a robot wrist at the end of the robot arm allows the end effector to be oriented independently of the robot arm. In essence, the addition of a wrist at the end of the robot arm increases the mobility and flexibility of the robot. The typical robot wrist consists of three rotational movements, as illustrated in Figure 12.

## 2.3 BASIC ROBOT COMPONENTS

Each robot system has four basic components: the manipulator (arm), the controller, the power supply, and the end effector. In addition, depending upon the design and use of the robot system, the robot system may also have sensory and mobility capability. Each of these components serves a fundamental purpose in the system design and overall system operation.

### 2.3.1 Manipulator

The manipulator (also called the robot arm) is that part of the robot which does the physical work. In general, robot arms in use today are stiff and heavy, limiting their flexibility and payload capacities. In addition, heavier arms are slower and less precise than lighter arms, but lighter arms tend to oscillate wildly when moved from one position (point) to another (7-39). Accordingly, these factors should be considered when considering and designing robot applications.

The performance of the manipulator is determined by the following parameters:

#### 2.3.1.1 Work Envelope

The robot arm gives the robot the capability to manipulate or handle different objects at any location within it's work envelope. The work envelope limits the volume (in space) within which the manipulator can effectively place objects (end effector). The size of the work envelope is limited by the size of the robot arm segments and the robot classification (discussed in section 2.2).

#### 2.3.1.2 Degrees of Freedom

Degrees of freedom refer to the number of axes on or about which the robot is capable of motion. Each of the four basic robot types (cartesian, cylindrical, spherical, and anthropomorphic) have three degrees of freedom, but this does not include any other axes of motion the robot (as a unit) may be capable of performing. Degrees of freedom consider all of the motions the robot is capable of performing. As an example, a spherical robot with the wrist pictured in Figure 12 would have six degrees of freedom (three for the robot arm, three for the wrist). A greater number of degrees of freedom would give the robot more flexibility and maneuverability, but at greater cost.

#### 2.3.1.3 Lifting Capacity

The manipulator is the main structural component of the robot system. The length and strength of the arm, as well as the speed at which the robot arm operates (moves), will dictate the maximum load which the manipulator can handle.

#### 2.3.1.4 Accuracy

For robot applications, accuracy is defined in two ways:

a. The tolerance between the actual and programmed locations of the end effector. Heavier arm components and payloads will cause deflections in the manipulator, as well as the momentum and inertia of the payload during movement. For precise operations, these deflections must be carefully considered during the design of the robot, then carefully controlled and monitored during operation.

b. The ability of the robot to place the end effector in the same programmed location with many repetitions of the same activity. This characteristic, called repeatability, is of utmost importance for robots used in manufacturing applications but may not be a significant factor for construction robots.

### 2.3.2 Controller

The controller is used to control manipulator movement, generating the necessary commands to move the manipulator arm and ensuring the end effector arrives at it's programmed location and performs its programmed task. In essence, the controller is the "brains" of the robot, receiving and interpreting the program commands and generating manipulator movement signals/commands. Manipulator control is generally achieved through the use of electronic devices and circuits, but may be classified as either open- or closed-loop controller systems. This classification is based upon the ability of the robot controller to receive and interpret information regarding the movement and position of the manipulator arm (i.e., whether the controller can receive and utilize feedback information).

#### 2.3.2.1 Open-Loop Control Systems

Open-loop control systems do not use feedback signals to monitor the movement and position of the manipulator. This is the simplest type of control, utilizing a fixed sequence of stops (mechanical or microswitch) built into the robot mechanical system to control the movement of the robot arm. In operation, robot movement during any sequence of the programmed task is terminated by a stop, triggering the start of the next sequence. Reprogramming for a different sequence of steps is generally difficult and time-consuming, as the stops must be relocated and calibrated for the new sequence of steps. This method of control is very well suited for the manufacturing industry, but, due to changing conditions and tasks, is generally not useful in construction.

2.3.2.2 Closed-Loop Control Systems

Closed-loop control systems provide a feedback loop (or signal) to the controller, allowing the controller to continuously monitor the movement and progress of the manipulator towards its programmed "target". With this type of control, the controller continuously compares the present position of the manipulator to its programmed target position, issuing corrective commands (as necessary) until the difference between the two positions is zero. Feedback information (and resultant control of the manipulator arm) may be achieved in a number of ways.

2.3.2.2.1 Remote Control

This method of control requires direct human involvement in the monitoring and control of the robot arm. Under this method, the operator performs all monitoring, feedback, and control functions. Other than basic safety commands or mechanical stops, preprogrammed commands or instructions do not exist in the robot controller system. In general, the operator may or may not be located in the immediate vicinity of the robot; if the operator is not in the immediate vicinity, electrical connections or radio communications are required for robot control. Teleoperation (the use of television cameras or other sensory equipment/devices to monitor the robot) is frequently used. This method of control is usually used under hazardous conditions, such as working with toxic materials or in dangerous environment. An example of this type of operation and control is the space shuttle robot arm; the operator is inside the space shuttle, monitoring the robot arm through a window in the crew deck.

2.3.2.2.2 Variable Sequence Control

This method of control uses a preprogrammed sequence of steps which may be changed from task to task, requiring the use of a computer. The computer is programmed through the use of a teaching pendant, a simple handheld device (resembling a calculator) for operating and programming the robot arm. The operator uses the teaching pendant to "walk" the computer (and manipulator) through the desired sequence of steps and tasks, storing critical points of the sequence in the computer memory. During operation, the computer uses this sequence of steps and critical points to monitor and control the manipulator; this is called point-to-point operation.

2.3.2.2.3 Off-line Programming

This method of control is similar to the variable sequence control method described above, except that the computer follows a sequence of commands written in a computer language. Programming of the controller is accomplished while the manipulator is not in operation. Manipulator operation will be either point-to-point or continuous path (smoother movement of the manipulator arm through the programmed task sequence).

2.3.2.2.4 Artificial Intelligence

Artificial intelligence is the ability of a computer to learn from and react to its environment. In general, this is similar to the growth and development of a child: as the child matures and interacts with its environment, it learns how to react to various stimuli. As an example, a young child may touch a hot pan or stove burner; after the first time, the child assimilates the pan and burner with heat (and pain) and will react accordingly.

With artificial intelligence, the controller is first programmed with "rules of behavior", following these rules while accepting signals from its environment and responding to those signals, then storing the signal and reaction for future use or reference. The controller receives signals from the environment through various sensory devices, including vision, acoustic, and contact transducers. With artificial intelligence, the controller becomes less of a computer, requiring and following a specific set of instructions, and more of an independent entity, learning to interact with its environment.

Present technology cannot sufficiently support advanced artificial intelligence. Artificial intelligence, when compared to the capabilities of a human, requires computers with large storage capacities (exceeding that of current mainframe computer systems), high speed processors (for the receipt, interpretation, comparison, reaction, and storage of signals from the environment), and the capability to operate in a real-time environment.

### 2.3.3 Power Supply

The power supply is that part of the robot that provides the force and energy to move the manipulator arm. Three types of power units are currently used in robotics: hydraulic, pneumatic, and electric. The type of power unit used with any robot system will be dependent upon the weight and size of the robot manipulator, the weight and size of the payload, the type of movements and operations required by the robot, the available energy requirements in the work area, and the available space for installing and storing the power unit.

#### 2.3.3.1 Hydraulic

Hydraulic power units use pressurized fluid (oil) to move the robot manipulator. In general, hydraulic power units are used to handle and maneuver heavy payloads, but at the expense of speed. The incompressibility of hydraulic fluid also permits very precise control of the robot manipulator. Hydraulic power units do have the following disadvantages: high operating pressures require heavier piping and valving systems, increasing the weight, cost, and complexity of the robotic unit; higher maintenance and repair costs; and leaks in the system could pose safety and environmental problems.

#### 2.3.3.2 Pneumatic

Pneumatic power units use compressed air for moving the robot manipulator. Operating pressures are lower than those found in hydraulic systems, preventing the handling of heavy payloads. Pneumatic systems are well-suited for areas and sites having an adequate supply of compressed air, but do have the following disadvantages: air used in pneumatic systems must be clean and dry to prevent internal damage to the pneumatic components, and these systems do not provide the same degree of control as hydraulic units. Pneumatic power units are typically used when hydraulic or electric power units may present safety concerns.

#### 2.3.3.3 Electric

Electric power units use electric motors and actuators (AC or DC) for moving the robot manipulator. Electric power units are significantly cleaner and quieter than hydraulic or pneumatic systems and are relatively inexpensive to build and maintain. Electric power systems are generally more accurate and have a higher degree of repeatability, but do not have the power and lifting capability of hydraulic systems. In addition, electric motors and actuators cannot be used in explosive of flammable environments; sparks from the electric components could spell disaster.

### 2.3.4 End Effectors

End effectors are those devices connected to the end of the wrist/manipulator arm with which the robot performs its designated task. In essence, end effectors are the "business end" of the robotic system; without the end effector, the robot would be useless. The performance of the end effector is governed by the positioning tolerance of the manipulator arm, the working tolerance of the specific tool in use, the performance of the sensor(s) monitoring the end effector's operation, and an adequate supply of material required for that specific operation. End effectors may be classified as either grippers or process tools.

#### 2.3.4.1 Grippers

Grippers are devices designed to lift and hold objects. Grippers may be fingered devices (some bearing a remarkable resemblance to the human hand), clamps, electromagnets, suction cups, or supporting structures (relatively broad and flat objects, such as shovels and buckets). Grippers are designed to accommodate the type and shape of material to be handled; for example, tube grippers, which handle pipes and tubes, resemble paper towel holders.

#### 2.3.4.2 Process Tools

Process tools are actual tools used to perform specific tasks or operations. Common examples of process tools include paint spray guns, welding guns, drills, and grinders. Process tools are also available to perform a variety of construction operations, such as spreading glue, mortar, or concrete, troweling concrete, sealing joints, or sand blasting.

The diversity in the types, characteristics, and performance of end effectors gives the robot system great versatility and flexibility in operation. End effectors are normally interchangeable, requiring little time and effort in replacing one end effector with another. Since no two end effectors perform the exact same task/operation, changing end effectors may necessitate reprogramming of the robot.

### 2.3.5 Sensors

Sensors are devices that convert information about the robot's environment (the physical world) into electronic signals that the control unit can read, process, and react to. In essence, sensors allow the robot to interact with its environment. The following are different types of sensors available in robotics.

#### 2.3.5.1 Tactile Sensors

Tactile sensors indicate physical contact between the robot (transducer) and another object. Tactile sensors may indicate contact only (the robot collided with another object) or indicate the extent and direction of force exerted during contact (allowing coordination and control during placement and assembly operations). Types of tactile sensors include:

2.3.5.1.1 Limit Switches

Limit switches provide simple tactile information through the use of microswitches or similar electro-mechanical devices. Contact with an object opens or closes an electrical circuit, causing the appropriate response by the robot.

2.3.5.1.2 Strain Gages

Strain gages detect contact and the force exerted during contact. Strain gages are generally simple electrical devices, such as wheatstone bridges, which measure changes in electrical resistance to calculate the force exerted during contact.

2.3.5.1.3 Potentiometers

Potentiometers measure contact force by measuring the displacement of one end of the sensor during contact. As an example, a sliding wiper (electrical) potentiometer would measure the change in voltage and/or resistance across the potentiometer during contact.

#### 2.3.5.1.4 Piezoelectric Pressure Transducers

These sensors measure the signals (or change in electrical resistance) emitted from special materials (quartz and ceramic are examples) while under pressure. These sensors may be used to determine the extent and direction of exerted force during collision. This information would allow the controller to guide the end effector during grinding, finishing, or insertion (assembly) operations.

#### 2.3.5.1.5 Tactile Sensor Array

A tactile sensor array is an array of tactile sensors, arranged in a grid pattern, for measuring pressure and force. Differences between sensors in the array would not only determine the extent of pressure/force being exerted, but would also indicate the contour, shape, orientation of the object. This array would emulate the human sense of touch, but accuracy would be dependent upon the number of sensors in a given area.

### 2.3.5.2 Proximity Sensors

Proximity sensors detect the proximity of objects before contact, allowing the robot to avoid collision. The proximity of objects is determined by measuring their location and/or distance from the robot. In this regard, proximity sensors are an important part of the navigation system installed on mobile robots. Types of proximity sensors:

#### 2.3.5.2.1 Sonar Sensors

Sonar sensors use sound (at ultrasonic frequencies, outside the range of human hearing) to detect the distance to objects. Sound waves are emitted by the robot and reflected by the object; the difference in time between emission and receipt of the reflected sound waves indicates the distance to the object. Sonar sensors may be used to measure coating thickness of paint or other applied substances (8-360).

#### 2.3.5.2.2 Electromagnetic Sensors

Electromagnetic sensors utilize the interruption of a generated (by the robot) magnetic field to note the proximity of an object. These sensors are generally effective only in measuring the proximity to metallic objects.

#### 2.3.5.2.3 Capacitative Sensors

Capacitative sensors utilize the interruption of a generated (by the robot) low power electrical circuit to measure the distance between the robot and an object.

2.3.5.2.4 Photoelectric Sensors

These sensors utilize either photoconductive or photovoltaic principles to determine the location to an object. Both principles utilize light emitters, reflectors, and receivers in operation. With photoconductive cells, a warning signal is sent to the controller when the light beam between the emitter and reflector is broken. With photovoltaic cells, the sensor reacts to emitted light that is returned by a reflector. In both cases, distance to objects and position of the robot (relative to the position of the reflectors) can be determined by triangulation (measuring the angles between three or more reflectors).

2.3.5.2.5 Laser Sensors

Laser sensors operate in the same manner as photoelectric sensors, with the exception of using laser emitters and receivers. Laser signals do not diffuse as much as light, giving laser signals longer operating distances.

2.3.5.3 Vision Sensors

Vision sensors are the most advanced of all robotic sensors. In general, vision sensors do not react to a single attribute of the object (distance, proximity, or contact), but conveys the entire image of the object to the controller. Vision systems utilize camera(s) to see the object, reacting to the light reflected by the object and converting the picture into electrical signals for use by the image processor and robot controller. Research in vision systems is currently centered in developing stereoscopic vision (similar to human vision); stereoscopic vision would give robots the capability to see in three dimensions and improving depth perception and object recognition.

2.3.5.3.1 Current Problems With Robot Vision

Although tremendous progress has been achieved in robot vision in recent years, it still lacks sufficient accuracy and resolution for use in the construction industry. Problems include:

2.3.5.3.1.1 Light Levels

The quality of vision is highly dependent upon the type and amount of lighting in use. In addition, high levels of ambient light and particulate matter in the air degrade vision quality.

2.3.5.3.1.2 Accuracy

With current vision system designs, the camera generates more data than the computer and image processor can process in real time. Consequently, the computer must perform data reduction techniques, which degrades vision quality and accuracy.

2.3.5.3.1.3 Slow Speed

Processing speeds are not fast enough to process the data generated by the camera. Without real-time information, the robot must slow its operations to prevent accidents. Real-time processing would be a advantageous for robot vision, but improvements must be made in computer software and processing speeds.

2.3.5.3.1.4 Capacity

The receipt and processing of vision data requires a significant amount of computer memory, surpassing that of most mainframe systems. New technology is required to increase the size of computer memory while reducing the size of the memory unit.

2.3.5.3.1.5 Cost

The research and development of vision technology has been expensive, and will continue to be expensive: continued development of robot vision will require significant amount of research and development funding and time.

### 2.3.6 Mobility

In most manufacturing and assembly applications, robotic systems are static: the robot is stationary and the work elements come to the robot. A stationary installation is unacceptable for construction purposes, since the robot must go to the worksite and operate in and around the jobsite. For this reason, robot research and development for the construction industry has focused not only on robot performance requirements (the tasks the robot performs), but also mobility.

In general, robot mobility is provided by tracks, wheels, legs, or a combination of the three. With current technology, speed is extremely slow (approximately 1.3 miles per hour) (8-365). For most applications, the robot is remotely controlled, with installed sensors and safety devices for collision avoidance.

Current research is centered upon developing autonomous navigation and collision avoidance systems for robots. These systems would allow a robot to maneuver without the direct control of a human operator, although human supervision should be maintained. Robots would move along either preprogrammed paths or have the capability to survey its work environment and plan its own path. Either capability would require a multitude and variety of sensors, ensuring the robot has active interaction with its work environment.

## 2.4 ADVANTAGES AND BENEFITS OF ROBOTS

As we have seen in the previous discussion, robots are complex systems. Although complex in design and operation, robots do present the following advantages:

### 2.4.1 Improved Product Quality

During operation, robot movements are very precise and accurate. It is common for robots to display a repeatability of .001 inch. This accuracy equates to higher product quality, satisfying customers and meeting their expectations. With satisfied customers, business should improve, with a commensurate increase in sales and profits.

### 2.4.2 Improved Quality of Life

The implementation of robots in the manufacturing industries has improved the quality of life for the workers. Robots have relieved workers of tedious jobs; humans tend to become bored and inattentive in such jobs, making them prone to accidents. Since the robot works without mental or physical fatigue, it can perform the job consistently and safely.

In addition to relieving human workers of tedious jobs, robots are increasingly employed in toxic and hazardous environments. As inanimate objects, robots are not susceptible to toxins or other materials that are hazardous to humans. One classic example: the reactor vessel at Three Mile Island was cleaned and repaired by robots, remotely controlled by human operators using teleoperation. Another example is the space shuttle robot arm, relieving astronauts of performing work in space (outside of the space shuttle).

#### 2.4.3 Reduction of Labor Costs

Robots are fully capable of working 24 hours per day, 7 days per week. Robots do not need coffee breaks, vacations, lost time due to illness, etc. Robots do not require wages or other compensation, fringe benefits, insurance, or pension accounts. Robots never question their assignments, never go on strike, and never vary their production rate. By maximizing the efficiency of their movements, robots may provide a productivity increase of 20 to 300 percent over human workers (in some industries and applications) (9-29).

### 2.5 DISADVANTAGES OF ROBOTS

As with all technologies and systems, robotics also has its disadvantages:

### 2.5.1 Lack of Mechanical Flexibility

In a comparison with the human worker, a robot is not nearly as complicated as a human; humans have more "end effectors" (arms, legs, fingers, etc.) and much more sophisticated sensory perception. In addition, the mechanics of robotics prevents robots from having the dexterity, physical flexibility, and movement of humans. This leads to a cardinal rule for implementing robots in the workplace: tasks must be optimized for the robot's capabilities and not for the sake of replacing human workers (10-63).

# CHAPTER THREE
# SOCIAL IMPLICATIONS

## 3.1 THE GENERAL PUBLIC

Whenever the word "robot" is mentioned, people tend to think of androids - machines with human features, including physical, logical, analytical, and, in most cases, emotional capabilities. This misperception is the direct result of the television and motion picture industries. How can one forget "Robbie the Robot" in Lost In Space, or C3PO in the Star Wars series? Both "robots", and virtually all other "show business" robots, are fictional, bearing no resemblance to actual robots in use today. This misperception, in and of itself, may pose no apparent problem for the implementation of robots in any application or industry, but subconscious public stigma may exist.

### 3.1.1 Lack of Understanding

In general, the average individual knows very little about robotics, its uses and potential in industrial applications, and the benefits of these uses. Very few people know or understand that robots improve productivity, relieve human workers of tedious, dangerous, or unpleasant tasks, and, in most cases, reduce the production costs of manufactured goods. Much of the information disseminated about robotics is published in technical journals and publications which are not available to the average individual. This lack of information causes individuals to formulate opinions and make decisions based on hearsay and emotion rather than logic and intelligence. These misinformed opinions and decisions, in turn, lead to bias and fear.

### 3.1.2 The "Human Touch"

Many people resent the fact that the products and services they receive may not have been produced or rendered by another person. In essence, they insist on that "human touch", knowing that another individual, just like them, made the product or performed the service. As examples, many people refuse to leave messages on telephone answering machines or use automatic teller banking machines. These devices provide service and convenience, but lack human interaction. Without the "human touch", users feel frustrated, exploited, and vulnerable.

### 3.1.3 Inferiority Complex

Many people fear the development of robots may ultimately lead to a time when robots will "rule the world." Again, this perception is largely manifested by the television and motion picture industries, where robots do become more advanced and capable of propagating themselves, eventually destroying the human race. With the development of artificial intelligence, the robot could have the capability to learn about itself and build more robots. At the present time, though, artificial intelligence is very primitive and technology cannot adequately support it. Research will continue in artificial intelligence, but it may be some time (25+ years?) before the requisite technology will be available. Even if the technology were available, robots could be programmed to prevent self-propagation and harm to humans.

### 3.2 THE DISPLACED WORKER

The implementation of robots in any organization or industry has but one purpose: cost reduction. Robots are installed to improve production efficiency and quality, thereby reducing cost. Since it is human workers who perform the work, one robot will replace one or more human workers and labor costs will be reduced. It is this threat of impending and potentially widespread unemployment that is of greatest concern to the work force.

With the development and implementation of robots, job security of the workers targeted for replacement is of primary concern. In most cases, it is the threat, not the action, of unemployment that causes the most harm. As robots enter the workplace, more individuals become fearful for their jobs, and could cause problems for management. These problems could include labor unrest, work slowdowns, or sabotage (of the plant or robots). It is up to management to ensure the integration of robots in the workplace is well-received and successful.

### 3.2.1 Employment Options for Displaced Workers

Recent studies have shown that unemployment is not a factor when robots are incorporated into the work environment; in fact, the number of jobs has increased. The implementation of robots gives the corporation/firm the following options for displaced workers:

#### 3.2.1.1 Early retirement

For those workers who are either eligible or reasonably close to eligibility for retirement, they are offered retirement. Retirement may be either voluntary or compulsory, usually at full benefits. A recent survey indicates that only 1.5 percent of workers displaced by robots were retired (11-486).

#### 3.2.1.2 Job Transfer or Retraining

Displaced workers may also be transferred to another job within the same company/organization. In this instance, the worker is offered another job, which may or may not involve the same tasks or level of knowledge his previous job required. In most cases, workers transferred to lower paying jobs retain their pay rate for a minimum amount to time, but may revert to a lower pay rate after expiration of this time period. According to a recent survey, 75.6 percent of workers displaced by robots were transferred to other jobs (11-486).

#### 3.2.1.3 Retraining for Robot-Related Work

Retraining for robot-related work. With the implementation of robots, individuals are still required to program, repair, and supervise the robot(s). Displaced workers are generally given preferential treatment in this type of work. Retraining can also shift workers to new careers. A recent survey indicated 5.8 percent of the workers displaced by robots were retrained for robotic management and operation (11-486).

#### 3.2.1.4 Termination of Employment

When considering the implementation of robots in existing industries and processes, the termination of employees should be the last resort. Extreme usage of this option will cause fear and discontent within the remaining work force. To date, this option has been exercised judiciously: only .2 percent of the workers displaced by robots have been terminated (fired or laid-off) (11-486).

The single-most important impact of robotics on the displaced worker will be the retraining of these workers to perform new, unfamiliar work. At first glance, retraining may not be a problem; for various reasons, however, workers may be reluctant to retrain and may resent the machines that have made their jobs obsolete. Reasons for worker reluctance toward retraining include:

a. A lack of motivation, caused by a poor self-image or outright fear of change. As an example, workers who have performed manual labor "all their lives" may resent retraining for desk jobs.

b. New jobs may not offer the same opportunities for advancement or recognition.

c. New jobs may decrease the interaction among the workers. In essence, these new jobs discourage or prevent the socialization and camaraderie among workers that may be evident on the production line.

d. New jobs may require less supervision. In general, human behavior tends toward having someone nearby to solve problems, correct mistakes, provide recognition, and provide emotional support.

## 3.3 CONCERNS OF LABOR ORGANIZATIONS (UNIONS)

At the present, unions do not favor the incorporation of robots in the work environment. The reason is very simple: the union's main function is work preservation and job security for its members. For this reason alone, no labor organization will endorse the incorporation of robots in the workplace.

Although they may not endorse the introduction of robots in the workplace, labor organizations do realize that the implementation of robots is rapidly expanding and necessary for maintaining a competitive edge. Without the use of advanced technology (including robots), firms cannot compete with those firms who do automate, resulting in economic collapse and loss of jobs. Accordingly, many labor unions insist negotiated agreements include provisions relative to the introduction of robots. As an example, a negotiated agreement may require advance notification of intended robot installation and use. These provisions help soften the impact of potential worker displacement.

## 3.4 FALLACIES AND MYTHS

Over the past thirty years, several fallacies and myths regarding the installation and use of robots have proliferated. These fallacies are generally the result of misinformation, misunderstanding, and, in some cases, outright lies.

### 3.4.1 Growing Unemployment

A popular belief holds that the increasing use of robots various industries will increase the unemployment rate. As noted above, this is untrue. In most cases, unemployment has been negligible. In addition, total unemployment is a direct function of real economic growth. Through higher productivity, robots can have a positive effect on economic growth, stimulating growth and employment.

### 3.4.2 Permanent Replacement of Human Workers

Another assumption is that robots will permanently eliminate the need for human workers in the workplace. This is untrue, for robots require human design, construction, programming, installation, maintenance, and supervision. As noted above, displaced workers would be the most likely candidates for retraining to perform these tasks.

## 3.5 SUCCESSFUL ROBOT IMPLEMENTATION

In one word, the key to successful installation of robots is communication. Without effective communication, management will be fighting an uphill battle against the attitudes of its workers and public opinion. Cooperation of the workers and the public (consumer/customer) is achieved with open and honest communication. Management must state why robots are necessary, and how robots will reduce costs, making the firm more competitive. In addition, management must present its plan for accommodating the worker who will be displaced by robots. If the plan envisions retirement, transfer, or retraining, management must state who is affected and offer other options.

Education is also essential to the smooth implementation of robots in the workplace. Adequate education will help eliminate the general misperceptions and misunderstandings about robots and their use in industrial applications. In addition, increasing the quality of basic, public education will help guide individuals away from manual jobs (which are prime targets for robotization) to more technical jobs. In essence, this is a form of proactive management, as the workers of tomorrow are trained for the skills that will be needed and guided away from potential areas of robotization.

## CHAPTER FOUR
## ECONOMIC CONSIDERATIONS OF ROBOTICS

### 4.1 GENERAL

The estimated cost for a construction robot is between $50,000 and $200,000, depending upon the size, type of end effector(s), control capabilities, and other operating characteristics. By no means is a robot considered a "cheap" investment. The purchase of a robot merits careful consideration and deliberation, considering its costs, potential benefits, impact upon the organization and work processes, and impact upon the firm's employees. This chapter will explore the economic considerations of robotics.

### 4.2 ECONOMIC EVALUATION TECHNIQUES AND MODELS

The purchase of a construction robot is considered to be a capital investment for the construction firm. Any investment, whether in terms of time or money, involves some amount of risk. Only through strict appraisal and economic feasibility studies can the inherent risk(s) be identified and mitigated. The most basic study is that of evaluating the costs and benefits of the proposed investment. Other methods of economic analysis are also available, such as the value estimation, payback, and return on investment methods.

A discussion of each method follows. To make the discussion realistic and relevant, all examples will relate to concrete finishing. The robot to be evaluated will be the Shimizu FLATKN concrete finishing robot (described in section 6.4.2.1), having an estimated purchase price of $100,000. The labor cost for one worker (cement finisher) is a straight labor wage of $26.18 per hour, including fringe benefits; when the cost of rented equipment (one trowel machine) is included, the labor rate becomes $30.78 per hour (12-92). Other pertinent cost factors and characteristics, when required, will be presented during the discussion of each analysis method.

## 4.3 COST AND BENEFIT ANALYSIS

The cost and benefit analysis compares the cost of the investment against its derived benefits (savings). With this method, the owner/user/investor can easily determine whether the investment is worthwhile. The results of this study are simple to interpret and understand: if the costs are greater than the benefits, the investment should not be made. If the benefits are greater than the costs, the investment may be beneficial, but additional economic analysis would be recommended.

Many of the cost factors and parameters for this analysis method are either readily calculated or may be accurately estimated. Information and data for these parameters is readily available, usually provided by the manufacturer at the time of purchase. Some parameters, however, are not based upon test results or data; as such, these parameters must be objectively estimated. In the event of uncertainty, it might be best to estimate unknown costs or benefits conservatively.

#### 4.3.1 Robot Costs

Certain costs will be incurred when purchasing and operating a robotic system. In general, these costs are either readily determined or may be estimated with a high degree of accuracy. These costs may be broken down as follows:

##### 4.3.1.1 Acquisition Costs

The acquisition cost of a robot is highly dependent upon the type of robot, the sophistication of movement and control, the type and movement of the end effector(s), and the number and sophistication of sensors. The acquisition cost will also include development costs. Development costs encompass all costs incurred by the robot manufacturer for designing and developing the robotic system. These costs include all labor, material, and facilities costs expended during researching, testing, and evaluating the robotic system.

#### 4.3.1.2 Investment Costs

Investment costs include the depreciation of the robotic system and equipment, and the interest charges on the investment. Depreciation is the decline in the robot's market value through age and use. Depreciation is based upon the useful life of the robot; for many construction robots, the useful life is conservatively estimated at 5 years. Depreciation may be calculated through a variety of methods, but once a method has been chosen, it must be continued over the life of the robot. Methods of calculating depreciation include straight-line, sum of the years digits, and (multiple) declining balance. The actual method for calculating depreciation should be based upon the owner's desires to recoup his investment and the anticipated annual usage of the robot. For instance, a specialized robot that will see limited use should be depreciated at a faster rate than a robot that will see significant use.

As stated before, the purchase price for any robot will be expensive and a loan would most likely be required. The interest costs, generally based upon the term and interest rate of the loan, must also be considered before purchasing the robot.

#### 4.3.1.3 Setup Costs

In manufacturing uses, setup costs include those costs for installing the robot and any of its support equipment. Since construction robots are mobile, permanent installation costs will not be incurred. Costs will be incurred while training personnel and testing the robotic system.

#### 4.3.1.4 Maintenance Costs

Maintenance costs include regular (scheduled and preventive) maintenance, system and equipment inspections, and repairs after breakdown. For production equipment operated continuously over two shifts, 10 percent of the acquisition cost serves as an adequate annual estimate of this cost. Although construction robots will probably not operate continuously, operation in harsh environmental and rugged workplace conditions will offset any difference.

#### 4.3.1.5 Operating Costs

Operating costs include the costs of electrical power, fuel, or other costs incurred during operation of the robotic system. In general, labor expended to operate the robot is not included as operating costs, but will be tracked as a separate direct expense. In construction, mobilization and demobilization of the robot is considered an operating expense.

### 4.3.2 Benefits of Robotization

In the cost and benefits analysis, benefits are those savings that may be derived from robotization. In general, the benefits derived from the use of a particular robot may be difficult to calculate or determine. These benefits may be classified as follows:

#### 4.3.2.1 Labor Savings

The ultimate objective of robotization is to replace workers with robots. When workers are eliminated, the expenses associated with this labor are also eliminated. Labor expenses include: direct wages and salary, fringe benefits, overhead (such as social security, unemployment, health insurance, etc.), and workman's compensation insurance. This direct replacement of labor will generate the most savings.

In addition, the increase in labor cost over a number of years will be greater than the increase in the robot operating cost. Figure 13 illustrates a comparison of the increase in labor costs versus the increase in robot operating costs. In this figure, the ordinate represents the hourly cost (both labor and robot) and the abscissa presents time in years. Labor costs will increase from cost of living raises and increases in fringe benefits, neither of which would apply to a construction robot. In essence, the increase in robot operating costs is relatively flat, while labor costs will increase significantly over time. Thus, over the economic life of the robot, labor savings should increase.

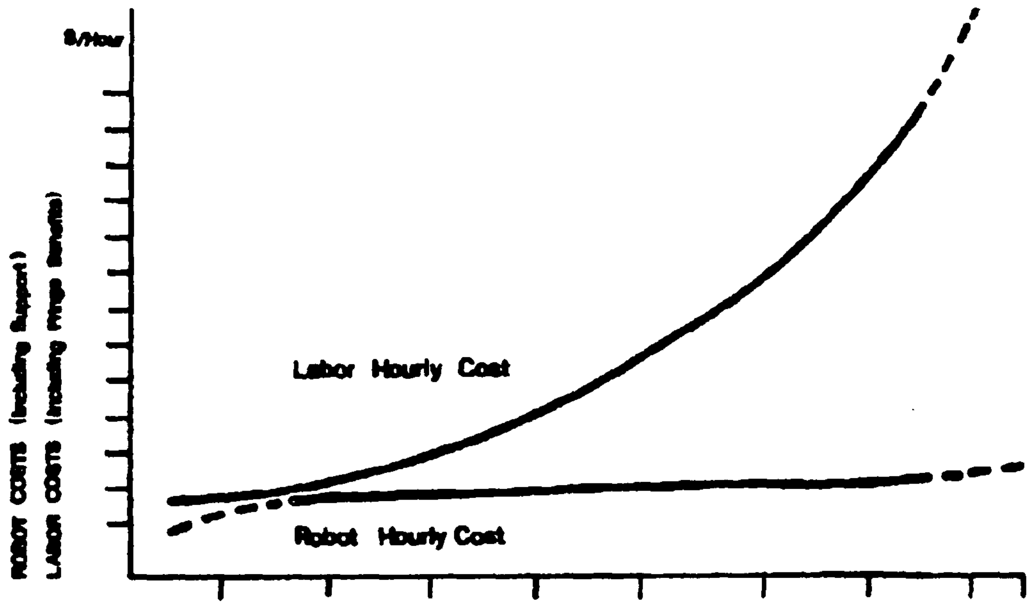



Figure 13 - Comparison Between Labor Costs and Robot Operating Costs

Source: Ref. #13 - Robotics: Applications and Social Implications

4.3.2.2 Increased Product Quality

Robots in the manufacturing industry (and those robots developed and tested in construction applications) have demonstrated the ability to produce higher quality products than human workers. Increased product quality results in material savings (the higher precision of work eliminates material waste), decreased cost for rework of defective or unsatisfactory work, and better performance of the finished product. In addition, higher quality may stimulate business (and generate more income) as satisfied customers return for additional work.

#### 4.3.2.3 Increased Productivity

Robots in the manufacturing industry (and those robots developed and tested in construction applications) have demonstrated increased productivity in completing work tasks and functions. Increased productivity reduces operating and labor costs and increases the amount of work the robot (and the process as a whole) may perform. For instance, suppose a robot can complete a work task in 50 hours, while a worker or crew may require 100 hours to perform that work. Not only is labor and other operating costs reduced, the remaining 50 hours are now available for other work. Thus, a direct benefit of robotization is the ability to take on more work and generate additional income.

Using the current example, the FLATKN is capable of finishing 400 square meters (approximately 4300 square feet) of concrete per day (14-285), while one worker with a trowel machine can finish 450 square feet per day (12-92). Assuming the FLATKN is working two shifts reduces its output in 8 hours to 2650 square feet per day, which is almost six times faster than the human worker.

#### 4.3.2.4 Elimination of Hazardous Conditions

Incorporating robots in hazardous, physically demanding, and strenuous work will reduce costs and improve working conditions. With robots performing this work, costs associated with insurance and workman's compensation may be reduced or eliminated, injuries may be reduced, productivity will increase, and fewer work stoppages will occur.

### 4.4 VALUE ESTIMATION METHOD

The Value Estimation Method compares the purchase price of the robot with the value of the robot to the user. The value of the robot to the user is determined by calculating the present worth of the net annual benefits derived by use of the robot over its economic life. These net benefits are the difference between the benefits of usage (savings in labor costs, higher productivity, better quality, and reduced hazards) and the costs of usage (operation, maintenance, and other expenses). This analysis method calculates the maximum price the owner/user should be willing to pay for the robot.

The Value Estimation Method considers the following parameters:

a. The purchase price of the robot ($100,000).

b. The economic life of the robot is assumed to be 3 to 5 years; the salvage value is assumed to be negligible ($0).

c. Robot operating time is assumed to be 6 hours per day, or 1500 hours per year. This allows for transfer, downtime, and repair time.

d. The real interest rate on the investment is assumed to be 7 to 10 percent. Considering an assumed inflation rate of 6 percent, the real interest rate corresponds to a market rate of 13 to 16 percent.

e. Annual maintenance costs were assumed to be $10,000 (10% of the purchase price). Maintenance costs include associated labor and material costs for maintaining and repairing the robot.

f. Annual operating costs should be estimated on information provided by the manufacturer. If information is lacking, an estimate of $1 per operating hour should be adequate.

g. Transfer costs are those costs associated with moving the robot between work areas. Assuming two workers expend one hour every two days in transferring the robot, an estimated annual cost would be $6545.

h. The amount of labor savings can be estimated only after a detailed design and review of the robotized work process. Robot/labor replacement ratios obtained from manufacturing industries are not directly applicable to the construction industry. Studies indicate that a replacement ratio of 1 robot per 3 workers is possible if the building design and project organization allow the robot to work uninterrupted for long periods of time (8-410). Labor costs include direct labor wages plus workman's compensation and fringe benefits. Annual labor hours are assumed to be 1700 manhours per worker.

i. The tax advantage of depreciation is also considered. As a tax-deductible expense, depreciation essentially increases the net income of the owner/user. Assuming straight-line depreciation over a service life of 5 years (a depreciation rate of 20% per year) and a tax rate of 38% yields a net increase in income of 7.6% of the robot purchase price per year.

#### 4.4.1 Value Estimation Method Example

The Value Estimation Method uses the following formula to calculate the value of the robot:

$$V = (kL - M - O - T + tP)\,\frac{(1 + i)^n - 1}{i\,(1 + i)^n}$$

Below is a description of the terms used in this equation, along with the values used in this example:

V = the discounted net worth of service over the economic life of the robot

k = the number of replaced workers (varies; see Table 1 below)

L = labor savings per year per one worker (at $30.78 per manhour over 1700 productive hours per year, the annual wage would be $52,326)

M = annual robot maintenance cost ($10,000)

O = annual robot operating cost ($1500)

T = annual robot transfer cost ($6545)

t = tax reduction rate (7.6%)

P = initial purchase price of the robot ($150,000)

i = interest rate (10%)

n = economic life of the robot (5 years)

Table 2 illustrates the value of the robot to the user for a varying number of replaced workers. Note that the value of the robot to the owner is in excess of $500,000 when three workers are replaced by the FLATKN robot. Of course, this is true only if the other parameters remain constant over the economic life of the robot. One advantage

| **Number of Workers Replaced (k)** | **Robot Value to User (V, in dollars)** |
|---|---|
| **1** | **158,762** |
| **1.5** | **257,940** |
| **2** | **357,119** |
| **2.5** | **456,297** |
| **3** | **555,475** |

Table 2 - Robot Value to User

Source: Ref. #8 - Industrialization and Robotics in Building: A Managerial Approach with this analysis method is its relative ease for computer programming, where the parameters may be easily varied and the results quickly obtained.

## 4.5 PAYBACK PERIOD ANALYSIS

In financial analysis, the payback period is that length of time required for the owner/investor to recover his initial investment in the robot. This method provides a quick calculation of the payback time, which may be used to decide if the robotic investment is worthwhile. Short payback periods provide positive incentive for robotic investment, whereas longer payback periods may inhibit robotic investment.

### 4.5.1 Payback Period Analysis Example

The formula for the Payback Period Analysis is:

$$P = \frac{I}{L - E}$$

where:

P = payback period (in years)

I = total capital investment in the robot. This includes the initial purchase price and any setup or installation costs.

L = annual labor savings generated by the robot, dependent upon the number of workers replaced by the robot.

E = total annual expenses for the robot

Using the same cost information from the Value Estimation Method:

$I = \$100,000$

$L = \$52,326$ (for one worker)

$E = \$18,045$ (\$10,000 + \$1500 + \$6545)

the payback period (P) is calculated at 2.92 years for one replaced worker. For two replaced workers, the payback period decreases to 1.15 years.

For a "quick and dirty" estimate of the potential of an investment in robotics, this method is satisfactory. Users are cautioned, however, that this method does not account for other factors, such as depreciation and interest costs, that will also affect the length of the payback period.

## 4.6 RETURN ON INVESTMENT EVALUATION

Whenever any firm or individual makes an investment, he is looking for a specific return on that investment. If that return is met or exceeded, the investment is considered good; if that return is not met, the investor may be dissatisfied and withdraw from the investment. The Return on Investment Evaluation gives the investor a simple method of determining whether the potential investment will meet his investment criteria before the investment is made.

### 4.6.1 Return on Investment Evaluation Example

The Return on Investment equation is:

$$ROI = \frac{(S - E)}{I} \times 100$$

where:

ROI = return on investment (in percent)

S = annual savings generated by the use of the robot, dependent upon the number of workers replaced

E = total annual expenses for the robot. With this method, depreciation is also included as an expense.

I = total capital investment in the robot. This includes the initial purchase price and any setup or installation costs incurred.

Using the same cost information from the previous analysis examples:

I = $100,000

L = $52,326 (for one worker)

E = $38,045 ($20,000 (depreciation) + $10,000 + $1500 + $6545)

the calculated return on investment is 14.28 percent. This return on investment, by any standards, is acceptable. In addition, the return on investment increases significantly with the replacement of more workers: when two workers are replaced, the return on investment increases to 66.61 percent.

## 4.7 OTHER FACTORS TO CONSIDER

It must be noted that these economic analysis methods are strictly preliminary planning tools. The actual return and profitability experienced after purchasing and using a robot will probably be different than that calculated during the economic feasibility analysis. This may be caused by any combination of several factors.

4.7.1 Questionable Accuracy of Input Variables

As with any analysis, the results are highly dependent upon the accuracy of the input values and variables. As stated previously, some variables can be estimated very accurately, provided the owner/investor has performed some measure of preliminary planning before the economic analysis. The remaining variables, though, are "best guesses" of robotic and economic performance in upcoming years. For instance, if the economic life of the robot were shortened to 3 years or the interest rate were to soar to 20%, different returns and economic measures would result. Therefore, the owner/investor is cautioned to use the economic analysis as a planning tool, not as a target or goal for economic performance.

4.7.2 Effective Labor Reductions

Each of the above economic analysis methods relate labor savings to the replacement of workers without considering the labor requirements for operating the robot. For instance, each of the above methods state some measure of economic performance based on the replacement of x number of workers, irrespective of the fact that the Shimizu FLATKN (and almost all robots) requires an operator to monitor and control the robot. This requirement, and its inherent costs, must also be considered. The labor costs for the robot operator may be considered in either of the following manners:

a. Add the cost of operator labor to the operating expense of the robot.

b. Include the robot operator as a displaced worker. For instance, when any of the above methods predict an economic performance based on one replaced worker, the owner/investor realizes that two workers must be removed from the production force (one to operate the robot, the other as a displaced worker).

If the labor costs for the robot operator are not considered, the economic analysis would produce questionable results.

#### 4.7.3 Economic Conditions

Before undertaking an investment in a construction robot, the owner/investor must determine current and predict future economic conditions. Is the local economy in a slump or booming? Will work be available in the future, particularly over the economic life of the robot? This is an important factor to consider, since it would be foolhardy to purchase a construction robot, then not be able to use it.

#### 4.7.4 Increased Productivity

Another factor that must be considered is the increased productivity of a construction robot. If a construction robot is purchased, will the firm be able to keep the robot productively employed? In essence, one robot hour does not equal one manhour. Consider the following: the Shimizu FLATKN robot is (conservatively) capable of finishing 2650 square feet of concrete in one day (eight hours). This same amount of concrete would require a crew of about six workers to complete in one day (eight crew hours, 48 manhours). If that crew of six workers had been productively employed over the entire year, the robot would be fully capable of replacing the entire crew with no significant impact or loss of productivity. If, however, only three workers are replaced and the construction firm maintains its historical annual workload, the robot would be productive for only 750 hours; approximately 750 robot hours would be available for additional work. This represents 750 hours the robot is available for work yet sits idle. If the robot is not working, it is not generating income that may be required to offset depreciation and investment costs. In order to increase the productive effort of the robot, the construction firm may wish to increase its workload.

## 4.8 SUMMARY

The above economic analysis aptly demonstrates the profitability and viability of robots in construction. In this analysis, the replacement of one worker results in modest return and profit. As more workers are replaced, the return and profitability increases substantially. The overall analysis is that the purchase of a construction robot would be a good investment provided a sufficient amount of work available.

CHAPTER FIVE
THE CONSTRUCTION INDUSTRY

## 5.1 ECONOMIC IMPACT

Construction is the largest industry in the United States, accounting for approximately 8 percent of the Gross National Product (1-196). In recent years, the volume of construction has exceeded 400 billion dollars annually. Construction also accounts for the direct employment of approximately 5.5 million workers (1-196), which represents approximately 6 percent of the non-agricultural labor force. In an overall perspective, construction accounts for the direct and indirect employment of approximately 14.5 million workers (approximately 16 percent of the non-agricultural labor force) (2-3). Indirect employment includes employees of material suppliers, transportation industries, construction material manufacturing industries, and other support trades and industries.

These figures indicate a significant investment, in terms of manpower and cost, in the construction industry. Any changes in the construction industry, whether good or bad, will have a profound effect upon the welfare of the country. These changes would affect the cost of living, cost of housing, and the capital investment in commercial enterprises.

## 5.2 FACTORS LIMITING ROBOT IMPLEMENTATION IN CONSTRUCTION

Over the past 30 years, the manufacturing industry has enjoyed increased productivity and reduced costs due to increased implementation of robots in the manufacturing process. To date, though, the construction industry has shown little interest in implementing robotic technology in the construction process. In general, this lack of interest is caused by the singular nature of the construction process: each construction project is unique, suiting the particular needs of the user (owner) and the environment, as perceived by the designer. This results in a number of limitations (when compared to manufacturing) restricting the implementation of robots in construction.

### 5.2.1 Dispersion of Work

In the manufacturing industry, the work is located in one location, typically called a workcell or workstation. In this workstation, the robot will perform the same task(s) or function(s) repeatedly, over an indefinite time period. In the construction industry, the work is dispersed over several projects and jobsites, with the work further dispersed within the individual jobsite. As such, a construction robot must be mobile (for movement within the jobsite) and transportable (for movement between jobsites). Robotic mobility has been developed and is widely used, usually under direct human control. Autonomous mobility (the ability of the robot to move without human input or control) requires the extensive use of sophisticated sensors and complicated navigation programs (software), significantly increasing the cost of the robot.

### 5.2.2 Repeatability

As stated in Chapter 2, the key to the success of robots in the manufacturing industry has been repeatability: the ability of the robot to perform the same task time and time again without input or adjustment by the operator. In the construction industry, the robot will perform the same task (type of work) time and again, but must be moved, aligned, and possibly reprogrammed between work areas. In addition, the lack of standardization in materials, finishes, quality, or any other factor (whether due to the owner's desires, environmental factors, or designer's prerogative) hinders repeatability.

### 5.2.3 Need For Multiple Trades and Crafts

In the manufacturing industry, a robot will perform its programmed task(s), regardless of the productivity of others. In the construction industry, any one construction project may consist of numerous independent, but interdependent, tasks or work functions. As an example, cement masons cannot place a concrete floor until after the carpenters have constructed and installed the formwork, the electricians and plumbers have completed their rough installations, and the steel workers have installed the reinforcing steel. Thus, one trade must wait for other trades to complete their work before performing its work. Current technology limits the capability for one robot to perform the work of all construction trades. As with human workers, robots performing different types of work would require close coordination and scheduling to complete the project.

#### 5.2.4 Conservative Attitudes

Through its history, the construction industry has been slow to adopt new ideas, technology, and techniques. Contractors and construction managers rely upon proven methods and materials in completing construction projects. Since every new product or technique will have a direct impact upon the contractor's ability to meet time schedules and quality requirements, these new products and techniques will undergo a lengthy (sometimes in excess of 10 years) trial period before adoption by one or more firms. In addition, these changes in products, technology, and techniques may require changes in the organization of existing processes, which would be resisted by the jobsite managers and supervisors, many of whom were former workers and intimately familiar with existing organizations and procedures.

### 5.2.5 Robot Flexibility and Adaptability

The adaptability, creativity, and flexibility of the human worker in the working environment cannot be overstated, and designers tend to take these factors for granted. For example, a designer may state on the plans to "field verify door dimensions and construct to fit"; if the door opening is too large, the carpenter will use shims in fitting the door to the opening. Artificial intelligence is required to perform this function, but that technology is still in its infancy. In addition, the physical dexterity and flexibility of the human worker cannot be duplicated by a robot. As a mechanical device, a robot has limited range of motion and work capabilities.

### 5.2.6 "Boom or Bust" Malady

Through history, the construction industry has reflected the economic condition of the country. When economic conditions are good, construction is booming and numerous construction projects are undertaken; when economic conditions are bad, construction slows and work is hard to find. This "boom or bust" condition prevents a steady source of income, particularly for small contractors and firms. Robots are not cheap and require a significant amount of capital investment. Human workers, on the other hand, do not represent a capital investment: when economic conditions are bad, workers may be laid off. Without a steady source of income, an investment in robots could be risky and difficult to justify.

### 5.2.7 Working Conditions

In the manufacturing industry, the robot's working environment is controlled. For instance, most (if not all) work is performed indoors, where the robot is sheltered from the weather. In construction, much of the work is performed outdoors, where robots may be exposed to the elements. Of particular concern would be moisture (rain, snow, ice, etc.) and temperature extremes (freezing temperatures). Moisture would damage electronic components and freezing weather would hinder robot performance and possibly cause damage. In addition, long-term exposure to sunlight could cause deterioration of robot components, particularly rubber and plastics.

In manufacturing, the robot's workstation is usually clean and free of clutter. In construction, jobsites are dusty, dirty, and cluttered with construction debris and materials. Dust and dirt will damage electronic components and clog mechanical components, inhibiting productive use and causing mechanical wear. Jobsite clutter and trash inhibits the robot's mobility, increasing moving times between work areas.

To prevent or minimize the effects of environmental conditions, construction robots must be built as air-tight as possible. Effective seals will prevent the intrusion of water and dust into the robot's electronic and mechanical components, extending the service life of the robot. Weather-tight construction will result in higher robot costs. In addition, an effective trash removal program and frequent cleaning of the jobsite would eliminate the clutter that prevents efficient robot movement.

## 5.3 FACTORS PROMOTING ROBOT IMPLEMENTATION IN CONSTRUCTION

Despite the limitations noted above, robots do possess certain advantages and potential for implementation in construction.

### 5.3.1 Increase in Productivity

The manufacturing industry has aptly demonstrated that the planned and efficient implementation of robots will increase productivity. Each of the below factors, individually and collectively, indicate ways that robots could increase productivity in construction.

#### 5.3.1.1 Continuous Activity

As previously stated, robots are capable of maintaining continuous and productive activity over long periods of time. Robots do not need coffee breaks, sick leave, vacations, or other nonproductive activities normally granted to human workers. Human workers are also subject to fatigue, while robots are not; in fact, robots are capable of increasing and maintaining the work pace. Under the right conditions (relating to job/task size, not environmental or time conditions), robots may be worked continuously for long periods of time. As an example, a concrete floor finishing robot may be operated on third shifts or in hot weather without any decrease in productivity.

#### 5.3.1.2 Work in Harsh or Unfriendly Conditions

As inanimate objects, robots are not seriously affected by adverse climatic or working conditions. During periods of high heat and/or humidity, human production will decline rapidly; such environmental conditions (if not absolutely extreme) will have no effect on robots. In addition, robots are fully capable of performing work in hazardous areas and with hazardous materials (paints, thinners, asbestos, etc.) which would restrict the productivity of human workers. Robots may also be used to perform monotonous tasks and functions; such tasks cause mental fatigue, boredom, and inattentiveness in human workers, none of which will occur with the robot.

#### 5.3.1.3 Decline in Productivity

Statistics in various countries indicate a decline in productivity in the construction industry over the past two decades, averaging 1.5 percent per year during the 1970s and early 1980s. This decline in productivity may be attributed to three factors: the increasing age of the labor force, the decline in working skills and knowledge, and the migration of workers (particularly younger workers) to more challenging and convenient jobs. (8-407) The combination of these factors results in most of the tedious and physically demanding jobs being performed by workers generally unskilled for the job. With unskilled workers, production slows to compensate for their lack of knowledge and skills. Unskilled workers also tax the industry's supervisory resources, as foremen and superintendents must devote more time to direct work supervision and less time to project management.

5.3.2 Better Quality and Workmanship

A problem that has been noted in the construction industry is the variation in quality between construction projects. Although the quality may meet minimum or industry standards, no two projects (even if performed by the same contractor) will possess the same level of quality. As stated previously, one of the advantages of robots is repeatability; repeatability ensures high quality standards are attained and maintained, providing higher and uniform quality over several construction projects. Higher quality will result in satisfied customers, which will further result in more business and income.

### 5.3.3 Reduction in Material Waste

Again, through repeatability, robots would utilize efficient methods and movements to perform assigned tasks, minimizing material waste. This, in turn, would reduce costs.

### 5.3.4 Safety Considerations

Perhaps the biggest factor for considering the use of robots in construction is safety. As noted in Table 3, the construction industry is the most hazardous industry in the United States. In a comparison with the manufacturing industry, construction accounts for seven times as many fatalities per worker and twice as many disabling injuries. (1-196) The major causes of accidents are falls from high work areas, materials falling on workers, crane and material handling accidents, and the collapse of trenches and excavations. Because of these accidents and overall safety record, workman's compensation insurance for the construction industry is extremely high; as an example, the workman's compensation rate for structural steel workers is 51 percent ($51 per $100 of payroll), although most other construction trades are well above 25 percent. The implementation of robots in high risk trades and tasks (although all construction trades, when compared with other trades and industries, may be considered high risk) will reduce insurance and safety costs. In the long run, it may be cheaper to damage or destroy a $150,000 robot than to provide medical care, lost wages, and rehabilitation for an injured worker.

| Industry Group | Workers (× 1000) | Deaths | | Disabling Injuries | |
|---|---|---|---|---|---|
| | | Total | Per 100,000 Workers | Total | Per 100,000 Workers |
| **All industries** | **100,100** | **11,300** | **11** | **1,900,000** | **1,898** |
| Service | 27,600 | 1,800 | 7 | 380,000 | 1,377 |
| Trade | 22,700 | 1,200 | 5 | 350,000 | 1,542 |
| Manufacturing | 19,000 | 1,200 | 6 | 330,000 | 1,737 |
| Government | 15,700 | 1,500 | 10 | 280,000 | 1,783 |
| **Construction** | **5,400** | **2,000** | **37** | **200,000** | **3,704** |
| Transportation and public utilities | 5,300 | 1,300 | 25 | 140,000 | 2,642 |
| Agriculture | 3,400 | 1,800 | 52 | 180,000 | 5,294 |
| Mining and quarrying | 1,000 | 500 | 50 | 40,000 | 4,000 |

Table 3 - Industry Death and Injury Rates

Source: Ref. #2 - Construction Contracting

## 5.4 CONSTRUCTION ROBOT PERFORMANCE CRITERIA

Chapter 2 presented the major features and capabilities of industrial robots. As noted in that chapter, those features and capabilities were presented from the manufacturing point of view, since robots are widely used in various manufacturing applications. The question to be examined now is: How are the principles of robotics applied to the performance of construction activities and tasks?

### 5.4.1 Construction Activities

The principles of robotics do not change from application to application, but the manner in which the robot is designed to suit its intended application does change. The first step toward implementing robots in the construction industry is to break a construction project into component activities. Table 4 lists ten basic activities present in a typical construction project. Each

| Number | Activity | Description | Examples of application |
|---|---|---|---|
| 1 | Positioning | Placing a large object at a given location and orientation | Erection of steel beams, precast elements, formwork, scaffolding |
| 2 | Connecting | Connecting a component to an existing structure | Bolting, nailing, welding, taping |
| 3 | Attaching | Positioning and attaching a small object to an existing structure | Attaching hangers, inserts, partition boards, siding, sheathing |
| 4 | Finishing | Applying continuous mechanical treatment to a given surface | Troweling, grinding, brushing, smoothing |
| 5 | Coating | Discharging a liquid or semiliquid substance on a given surface | Painting, plastering, spreading mortar or glue |
| 6 | Concreting | Casting of concrete into molds | Casting of columns, walls, beams, slabs |
| 7 | Building | Placing blocks next to or on top of one another with a desired pattern | Blocks, bricks, or stones masonry |
| 8 | Inlaying | Placing small flat pieces one next to the other to attain a continuous surface | Tiling, wood planks, flooring |
| 9 | Covering | Unrolling sheets of material over a given surface | Vinyl or carpet flooring, roof insulation, wallpapering |
| 10 | Jointing | Sealing joints between vertical elements | Jointing between precast elements, between partition boards |

Table 4 - Basic Construction Activities

Source: Ref. #8 - Industrialization and Robotics in Building: A Managerial Approach

of these activities is defined so that a single robot, with the same end effector and mode of operation, could perform the activity. Each activity is then analyzed to determine the performance requirements for the following robot components:

a. Manipulator performance (reach and payload).

b. Type of end effector and its performance characteristics.

c. Material supply (to the robot) procedures and process.

d. Type and level of control required for the robot and its operation.

e. Sensor requirements.

f. Mobility requirements.

It should be noted that many tasks require the performance of more than one basic activity. For instance, the installation and finishing of wallboard would require the following activities:

a. Positioning of the wallboard.

b. Connecting the wallboard (to the partition framing), including taping.

c. Coating the taped joints.

d. Finishing the taped joints.

e. Coating (painting) the wallboard. (8-372)

Therefore, it is readily apparent that more than one robot may be required to complete one construction task. It is this complex nature of the construction process that makes robot design difficult and expensive.

### 5.4.2 Generic Construction Robot Configurations

Based upon a detailed analysis of the basic construction activities and requisite robot performance characteristics, four generic robot configurations ("families") were identified. (8-372) Each family could perform a specific group of basic construction activities, with each family comprised of many robot types that utilize different end effectors, sensors, control units, and material supply systems to perform programmed tasks and activities.

#### 5.4.2.1 Assembly Robot

This type of robot, schematically presented in Figure 14, is used to haul and position large building components, such as steel beams, precast concrete members, and partially assembled building components. The basic configuration for this type of robot would be an anthropomorphic (jointed) arm, similar in appearance to existing types of construction equipment (cranes, excavators, concrete pumps, etc.). The main difference between this type of robot and existing construction equipment would be the robot wrist, which would give the robot additional capability and flexibility in payload (component) orientation. Since this robot will handle large and heavy structural members, it should be designed with a reach of 65 to 100 feet and a payload of 1 to 5 tons.

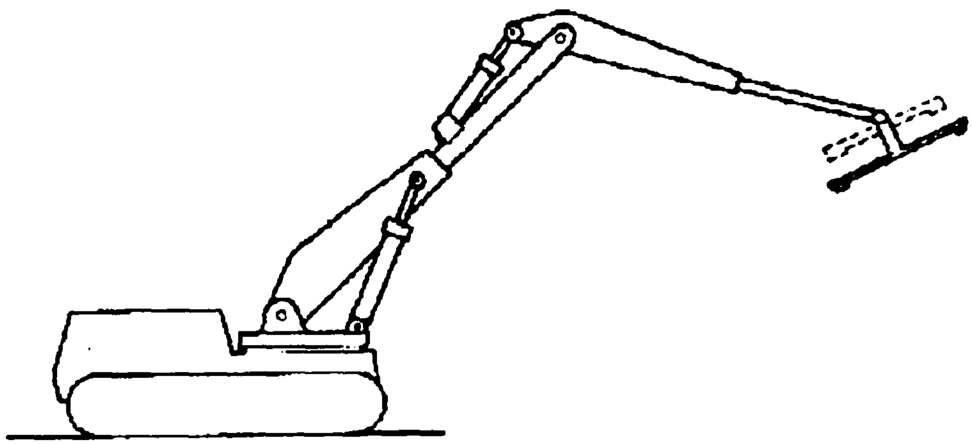


Figure 14 - The Assembly Robot

Source: Ref. #8 - Industrialization and Robotics in Building: A Managerial Approach

Control of the robot may be performed by preprogramming the required robotic movements and tasks or remote control. Various types of grippers would be used, such as finger hooks, magnetic grippers, vacuum grippers, or pipe grippers, depending upon the type of object that will be handled. The robot would be capable of performing its work in a one position, or moving around the worksite on wheels or tracks; movement would most probably be under direct human control.

The need for human assistance in manipulating the payload would be highly dependent upon the control capabilities of the robot. The most basic robot should be able to attach loads without human assistance, which would require self-attaching grippers. A more sophisticated controller would allow the robot to locate, identify, and lift loads without human assistance. The most sophisticated robot would be able (in addition to the above) to orient and connect the payload to the structure; this would require special sensors and end effectors. The use of this type of robot would eliminate the need for human workers on the structure, which is the most dangerous work (having the highest workman's compensation insurance rate) in the industry.

Although this type of robot may be used in most any conditions and circumstances, it would best be utilized in harsh or hazardous conditions. Under these conditions, the robot must be capable of full operation without direct assistance or control by a human operator or worker.

5.4.2.2 Interior Finishing Robot

This type of robot, schematically presented in Figure 15, may be used to perform a number of interior finishing operations, such as painting, plastering, fireproofing, jointing, etc. All of these activities would require a considerable degree of accuracy and precision. In general, one type of robot would be developed for performing a specific operation with limited capability for reprogramming and retooling for other types of work. Multifunctional robots are possible, but would require separate end effectors and material supply systems to meet each task; this, in turn, increases the size, weight, and cost of the robot.

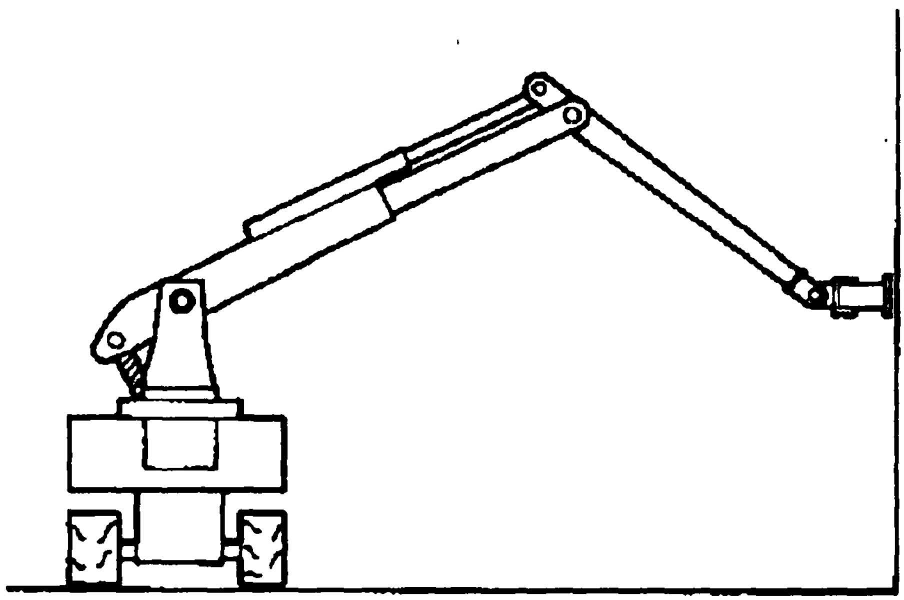


Figure 15 - The Interior Finishing Robot

Source: Ref #8 - Industrialization and Robotics in Building: A Managerial Approach

The dimensions of the interior space(s) that require work would control the size of the robot's manipulator arm and work envelope. In general, the larger the work envelope of the robot, the more work the robot may perform from one location; less movement would result in higher productivity. It should be noted, however, that a longer manipulator arm (and a larger work envelope) would result in a heavier and more expensive arm and a higher live load on the floor. The design of this type of robot must consider the costs and benefits between a larger arm and the efficiency of a larger work envelope. In general, a manipulator reach of 8 to 14 feet and a lifting capacity of 20 to 30 pounds would be adequate for performing virtually all interior finishing operations.

The end effector for this type of robot would be dependent upon the type of work to be performed. Common end effectors include welding guns, paint spray guns, grippers, nail guns, and caulking dispensers. Material supply would also depend upon the type of operation being performed and the type of material being used in the operation. For most operations, such as painting, plastering, or caulking, material would be stored in external modules and pumped to the end effector.

For the basic robot, the control unit must control the operation and manipulation of the end effector. The sequence of operation for the manipulator may be preprogrammed into the controller through either off-line programming or the use of a teaching pendant. Future developments may allow the use of artificial intelligence or highly developed sensory control to allow the robot to determine its work area and environment without human input. At present, the accuracy of operation is highly dependent upon the level of sophistication of the sensors and control unit.

This type of robot must also be mobile. Movement between work stations may be performed automatically (autonomously) or by direct human control; movement would be on either wheels or tracks. Such autonomous movement would require a navigation and anti-collision ability, with the requisite sensors and control capability. If the robot is designed to move autonomously, its path should be clearly marked for easy identification by the robot's sensors and human workers.

#### 5.4.2.3 Floor Finishing Robot

The floor finishing robot, schematically shown in Figure 16, is designed to perform continuous finishing operations over large horizontal surfaces. Finishing operations include troweling, sanding, grinding, smoothing, and joint filling.

The end effector for this type of robot is located beneath the robot. The end effector itself possesses limited capability for movement, generally in the vertical axis (it may be raised or lowered) with no

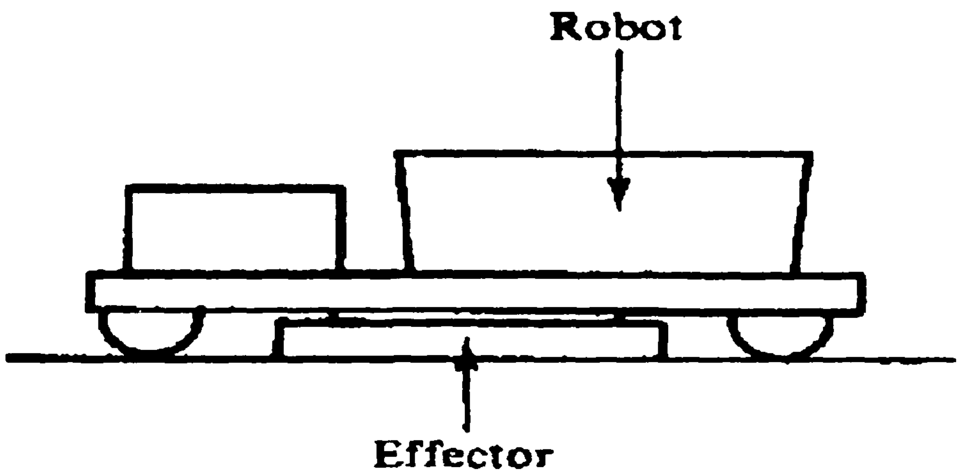



Figure 16 - The Floor Finishing Robot

Source: Ref #8 - Industrialization and Robotics in Building: A Managerial Approach

capability for horizontal movement. The vertical movement of the end effector controls the quality of the work performed by the robot. Horizontal movement of the end effector is provided by movement of the entire robot platform and/or carriage.

Since these operations are, in general, simple and continuous, the robot performs its work while moving. Mobility is provided through either tracks or wheels. Control of the robot's movement is accomplished through either remote control or preprogrammed patterns. If the robot is capable of autonomous movement (preprogrammed work patterns), the control unit must be able to navigate the robot through its preprogrammed route and the robot must have anti-collision sensors.

5.4.2.4 <u>Exterior Wall Finishing Robot</u>

The exterior wall finishing robot, shown schematically in Figure 17, is designed to finish large vertical surfaces. Typical operations include painting, jointing, plastering, and wall inspection.

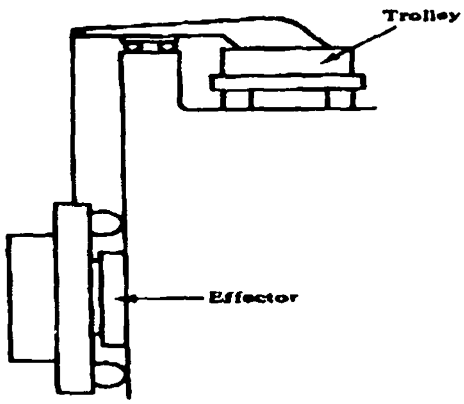



Figure 17 - The Exterior Wall Finishing Robot

Source: Ref #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

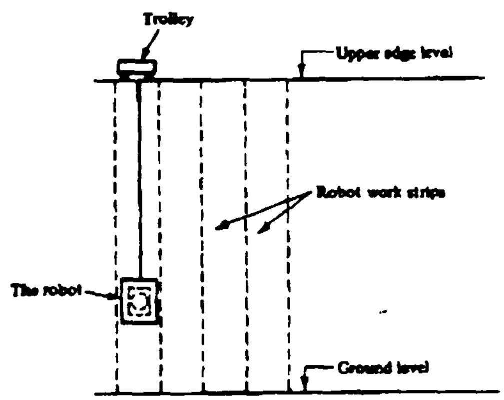



Figure 18 - Exterior Wall Finishing Robot Work Pattern

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

This type of robot consists of two major components, the carriage and trolley. The carriage is suspended from the roof and is connected to the trolley by a rope or cable. The carriage travels up and down the suspension rope or cable, allowing the work to be performed in vertical strips (see Figure 18). As each strip is completed, the trolley moves horizontally to the next strip. This type of robot may be either remotely controlled or preprogrammed for autonomous execution of its tasks.

The end effector is mounted on the carriage, between the carriage and the wall. The end effector may have some freedom of movement in the horizontal and vertical directions, dependent upon the type of operation being performed and the width of the work strip. Positioning of the end effector may be accomplished through the use of other devices (grippers or spacers) attached to the carriage.

# CHAPTER SIX
# CONSTRUCTION ROBOTS IN SERVICE

## 6.1 GENERAL

In the previous chapter, the four generic families of construction robots were analyzed and discussed. Within these four generic families, several types of robots have been developed and are in use throughout the world, although few robots are currently in use in the United States. This chapter will present these robots, grouped by generic family, and discuss their operating characteristics.

## 6.2 ASSEMBLY ROBOTS

As stated in the previous chapter, assembly robots are used for the lifting and positioning of building components. In general, these types of robots will resemble existing construction equipment (cranes, excavators, etc.) and are primarily used for weight lifting/material handling operations. This family also contains a few "unique" types of robots, such as a concrete distribution robot, which will be discussed shortly.

### 6.2.1 Extended Multi Joint Robot (EMIR)

The Extended Multi Joint Robot (EMIR) is a multi-link articulated boom crane currently under development by Kernforschungszentrum Karlsruhe (KfK) and sponsored by the government of West Germany. Figure 19 presents a schematic diagram for this robot.

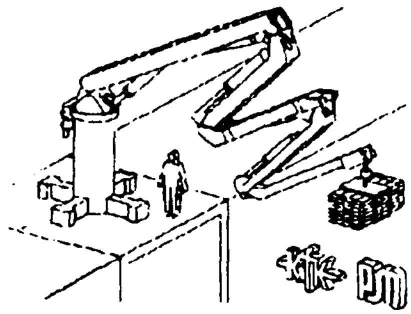


Figure 19 - Extended
Multi Joint Robot (EMIR)

Source: Ref. #15 -
Proceedings of the 5th
International Symposium
on Robotics in
Construction

The robot manipulator is a jointed arm mounted on a conventional crane carriage (either mobile or stationary) with 360 degree rotational capability. The arm has five hydraulically actuated joints, with all arm joints capable of rotation in the vertical plane. This arrangement allows the arm to bend around horizontal obstructions, giving the robot better control of its payload during operation. The tip of the boom is capable of accommodating different types of end effectors, allowing this robot to perform a number of tasks, such as steel erection, material handling, fire fighting, concrete placement, and others. This robot has a spherical work envelope with a radius of 22.2 meters (approximately 67 feet) and is capable of handling a payload of 1400 kilograms (approximately 3100 pounds) (15-626).

This robot may be controlled either manually or automatically. Under manual control, the operator guides the manipulator with a joystick. Programming for automatic control may be performed either off-line or with a teaching pendant. During operation, whether in remote or automatic control, the robot controller performs automatic trajectory planning (for the end effector) and collision avoidance. This robot does not have sensors for tracking the position of the manipulator arm, but relies upon an internal navigation software to accurately plot the "target" and obstacles.

#### 6.2.2 Steel Erection Robots

The Shimizu Corporation of Japan has developed two types of robots for the erection of structural steel building components: the Mighty Jack and the Mighty Shackle Ace. The Mighty Jack was developed in 1985 and is capable of lifting and placing up to three structural beams at one time. The Mighty Jack requires a crane to lift it (and the structural components to be placed) into position; once in position, the Mighty Jack places the beam(s) automatically, relieving the crane for other work. After placing the beams, the crane lowers the Mighty Jack for attachment of the next components to be placed.

The Mighty Shackle Ace is a radio controlled auto-release clamp used in the placement of structural steel components. Figure 20 illustrates the Mighty Shackle Ace in operation; Table 5 lists its specifications. During operation, the Mighty Shackle Ace serves as an "interface" between the crane and the structural component it carries. After the structural component has been lifted and workers have fixed it in place, the Mighty Shackle Ace releases the component (unlocks and opens the clamps) and the crane proceeds to attach and place the next structural component. The use of the Mighty Shackle Ace relieves human workers of

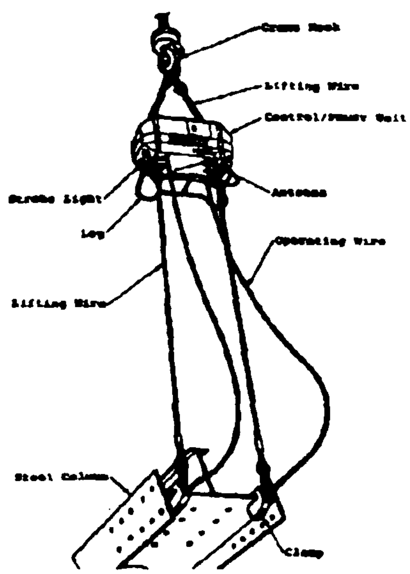



Figure 20 - Shimizu Mighty Shackle Ace

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

| | |
|---|---|
| Dimensions | width 415 mm<br>length 950 mm<br>height 965 mm |
| Weight | 250 kg (clamp 12kg) |
| Lifting capacity | 12 tons (15tons) |
| Power source | Battery (12V x 2) |
| Lock system | A double locking mechanism<br>1 link lock<br>2 pin lock |
| Control system | Wireless Remote Control<br>Effective distance = About 60m |

Table 5 - Shimizu Mighty Shackle Ace Specifications

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

climbing steel components to release crane loads, significantly reducing the time for structural steel erection and increasing worker safety.

### 6.2.3 Concrete Distribution Robots

The Takenaka Corporation of Japan has developed a robot, called the Horizontal Concrete Distributor (HCD), for the placement of concrete over a horizontal surface. In general terms, the robot arm performs two functions: it supports the hose that supplies concrete pumped to the site of the work and it controls the position of the discharge from the concrete hose. The robot manipulator has an overall length of 20 meters (approximately 63 feet) and has placed 340 cubic meters (approximately 450 cubic yards) (16-546) of concrete in one day. The use of this robot reduces labor requirements for, expedites, and standardizes the concrete placement process.

The robot consists of a multi-link manipulator having four joints capable of rotation in the horizontal plane and two joints capable of rotation in the vertical plane. Rotation of the four joints in the horizontal plane allows the robot to avoid vertical obstructions (columns, partitions, piping, etc.). The joints which allow rotation in the vertical plane are located near the hose discharge, permitting the robot to avoid horizontal obstacles (piping, beams, reinforcement steel, etc.). Each joint is hydraulically actuated. Figure 21 schematically illustrates the HCD in operation. Table 6 lists the specifications for this robot.

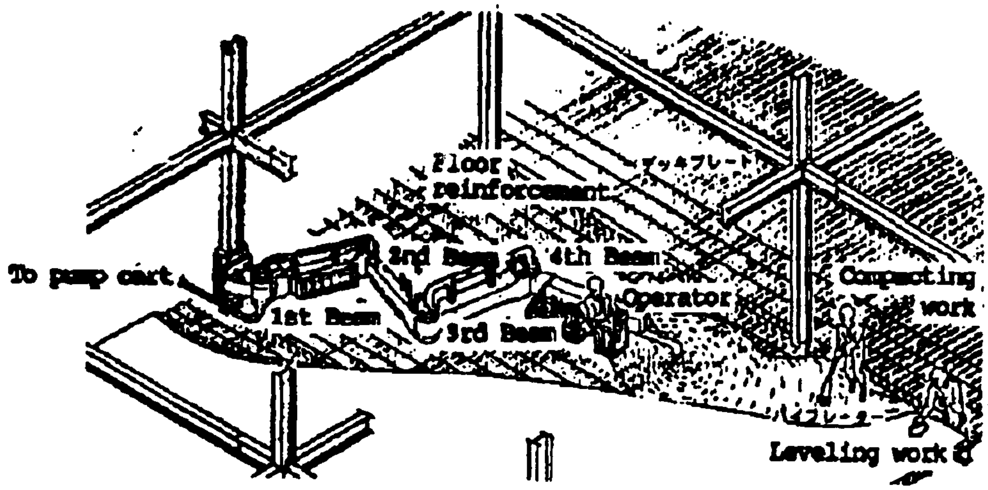



Figure 21 - Takenaka Horizontal Concrete Distributor

Source: Ref. #16 - Proceedings of the 5th International Symposium on Robotics in Construction

This robot may be either manually or automatically controlled. Under manual control, the operator is required to operate each joint separately. For work locations with minimal obstructions, this method of control is satisfactory; for obstructed locations, this method of control is tedious, slow, and mentally fatiguing. With automatic control, the operator still controls the movement of the manipulator, but this control is achieved through the use of one joystick and software that positions each beam. Obstacle avoidance is achieved through the use of preprogrammed obstacle locations and ultrasonic sensors.

The following safety features are incorporated on this robot:

a. Strip touch (pressure) sensors located on the underside of the third and fourth beams. Touching any one of the sensors stops the robot.

b. Each of the beams is limited to moving at .6 to .7 meters per second.

c. Flashing lights and buzzers warn workers of movement of individual joints.

In addition to the horizontal concrete distributing robot described above, vertical concrete distributing robots

| | |
|---|---|
| Total length | 20 m ( beams: 4 m,7 m ) |
| Weight | 3,500 kg/800 kg |
| Hose gage | 125 mmφ |
| Joint drive | Hydraulic motor |
| Operation | Manual : 4 levers<br>Automatic : 1 lever |
| Sensor | Touch sensor<br>Rotary encoder |
| Power unit | 5.5 Kw, 3-ph 200 V |
| Working area | about 1,000 $m^2$ |

Table 6 - Takenaka Horizontal Concrete Distributor Specifications

Source: Ref. #16 - Proceedings of the 5th International Symposium on Robotics in Construction

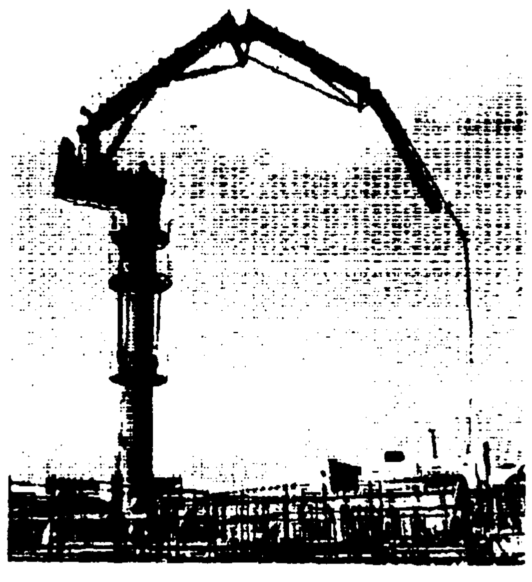


Figure 22 - Takenaka Concrete Distribution (CONDIS) Crane

Source: Ref. #17 - <u>Robots - Automation of Construction</u>

have also been developed by the Takenaka Corporation and the Ohbayashi Corporation. In appearance and operation, these robots are very similar to the EMIS discussed in section 6.2.1. The Takenaka Corporation robot is called the Concrete Distributing (CONDIS) Crane and is shown in Figure 22. Although designed primarily as a concrete distributor, this robot's joints may be locked for weight handling operations.

### 6.2.4 Reinforcement Steel Placement Robots

The Kajima Company and Takenaka Corporation are two companies who have developed reinforcement steel placement robots. The Kajima robot looks very similar to a hydraulic excavator with a gripper instead of a bucket. The Takenaka robot looks very similar to a crane; see Figures 23 and 24. Both robots are used for horizontal and vertical placement of long and heavy steel reinforcement bars in a preprogrammed pattern. Both robots provide significant reductions in production time and manpower.

### 6.2.5 Masonry Construction Robots

In recent years, significant research has been conducted in the application of robotics in masonry construction. Much of the research has been very elementary, programming robots to stack masonry units without mortar or reinforcement. Without the structural

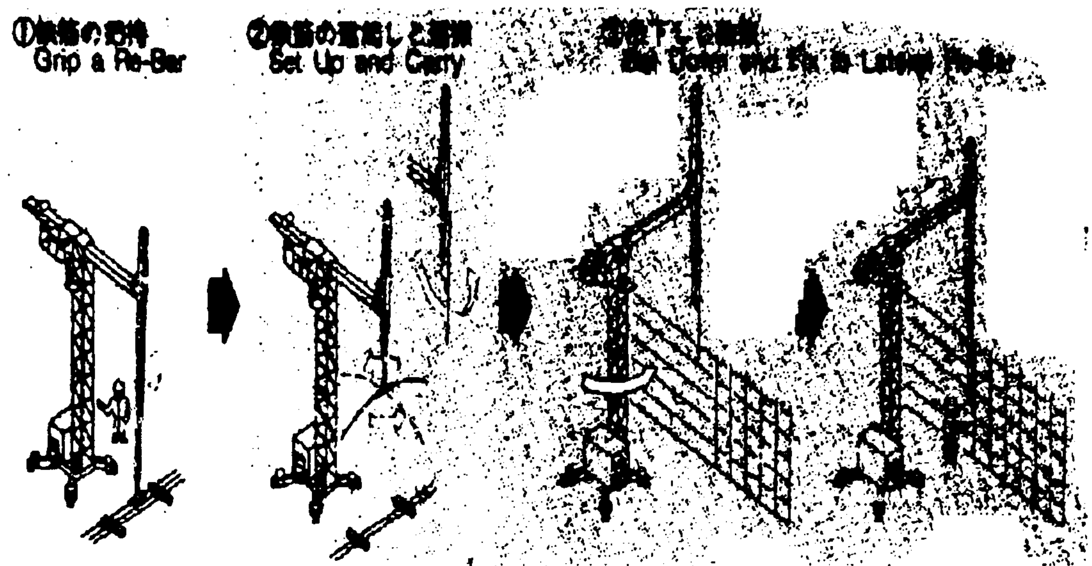



Figure 23 - Takenaka Rebar Placement Robot Operation

Source: Ref. #17 - Robots - Automation of Construction

integrity of mortar or reinforcement steel, though, these walls are of questionable quality and value.

In Japan, the Ministry of Construction and the Science University of Tokyo have jointly developed a structural wall erection system called Solid Material Assembly System (SMAS). This system was specifically developed for robotic construction. SMAS utilizes standard masonry construction components, consisting of precast concrete and cross-shaped steel reinforcement inside of each component. The masonry units are automatically positioned by a robot (see Figure 25), with the robot mechanically joining vertical reinforcement members between units of adjacent rows; horizontal reinforcement is provided by overlapping bars between adjacent components. After a one story wall has

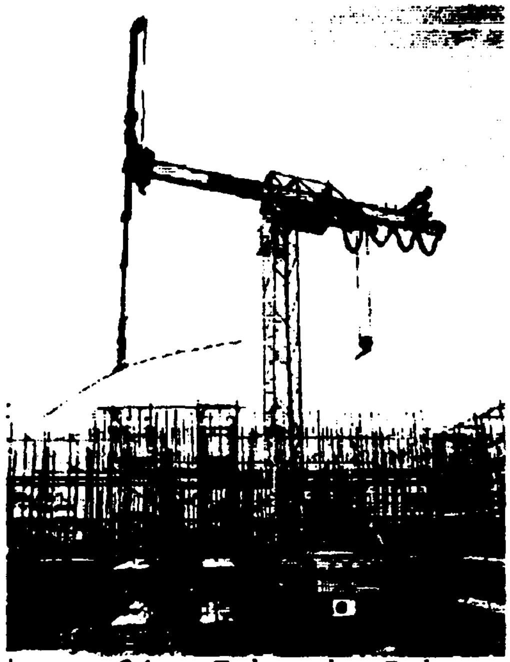


Figure 24 - Takenaka Rebar Placement Robot

Source: Ref. #17 - Robots - Automation of Construction

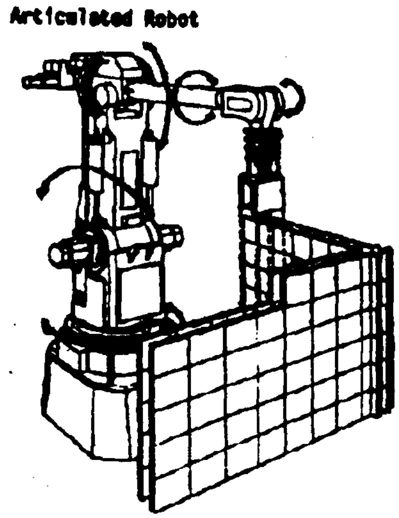



Figure 25 - Robot Wall Erection System

Source: Ref. #18 - Proceedings of the 5th International Symposium on Robotics in Construction

been erected by the robot, the wall is grouted from the top, providing structural integrity and support.

The robot itself is a classic jointed-arm robot mounted on rails for mobility. The locations and layout of the material supply piles and the stacked wall are preprogrammed into the robot controller. During operation, the robot uses navigation hardware to track depletion of the material supply pile and progress of the stacked wall, with touch sensors to verify and position individual masonry components. During production testing, the robot exhibited a "cycle time" (picking up one component and stacking it) of slightly under one minute (18-447). When compared to standard manual masonry construction, this seems excessive; but one should remember that this system includes the installation of vertical and horizontal reinforcement.

## 6.3 INTERIOR FINISHING ROBOT

As discussed in section 5.4.2.2, interior finishing robots perform a number of interior finishing tasks. In general, these robots are very flexible, dexterous, and mobile.

### 6.3.1 Fireproofing Robots

In the construction industry, the application of fireproofing material to structural components is considered to be one of the most unpleasant tasks. The Shimizu Corporation has taken an active interest in developing robots to perform this work, with the SSR-3 being the latest model. The SSR-3 is designed to spray a mixture of rockwool and cement fireproofing on structural steel members.

The SSR-3 consists of a mobile vehicle, a jointed-arm manipulator, a distance sensor assembly, and a controller. Mobility is provided by two drive wheels located at the center of the vehicle; the vehicle is capable of movement in any horizontal direction. The manipulator is approximately 2 meters (approximately 6.5 feet) in length with a spray gun attached to the end. The distance sensor assembly utilizes two ultrasonic sensors mounted at the top of a telescopic pole. With this distance information, the controller can maintain a uniform distance between the steel member and spray nozzle (precision of +/- 3 mm) (8-381), even when the robot is in motion. The controller is programmed either off-line or with a teach pendant. Figure 26 presents a schematic diagram and Table 7 lists the specifications of the SSR-3 system.

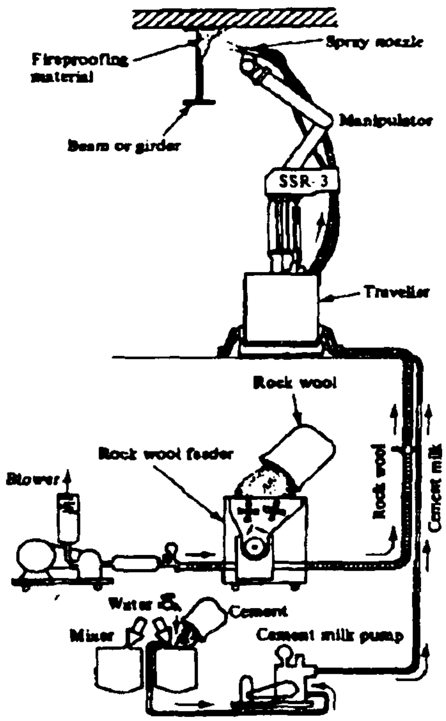



Figure 26 - Shimizu SSR-3 Fireproofing Robot

Source: Ref. #8 - Industrialization and Robotics in Building: A Managerial Approach

| | | | |
|---|---|---|---|
| [illegible] | | Degrees of freedom | 2(traveling, revolution) |
| | | Positioning | DC servo motor |
| | | Traveling speed | max. [illegible]m/min |
| | | Positioning precision | ± [illegible]mm |
| Manipulator | | Degrees of freedom | 4 |
| | Speed | Forward-backward turning | max. [illegible]/sec |
| | | Up-down turning | max. [illegible]/sec |
| | | Right-left swing | max. [illegible]/sec |
| | | Up-down swing | max. [illegible]/sec |
| | | Load capacity | max. [illegible]kgf |
| | | Positioning | DC servo motor |
| | | Positioning precision | ± [illegible]mm |
| | | Variable height | max. [illegible]mm(manual) |
| Control functions | | Teaching functions | .PTP<br>.Manual data input<br>.Data input from cassette tape |
| | | Display<br>Memory capacity | 9"CRT and LED monitor<br>master program [illegible]<br>block program [illegible]<br>pattern program [illegible]<br>[illegible]patterns |
| | | Position correction function | position correction by ultrasonic sensor |
| | | External signal | 6 points |
| Others | | Safety function | falldown prevention switch×[illegible]<br>bumper switch×2<br>emergency switch×[illegible] |
| | | Dimensions | length [illegible]mm<br>width [illegible]mm<br>height [illegible]mm |
| | | Weight | [illegible]kg |
| | | Temperature | 0-40°C |
| | | Power source | AC100V,50/60Hz,[illegible] |

Table 7 - Shimizu SSR-3 Fireproofing Robot Specifications

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

During productivity testing, the SSR-2 robot (the predecessor of the SSR-3) required 36 hours of work and 15 hours of travelling per 100 units of output, compared to 86 hours required by a skilled human worker (8-381). This represents a productivity increase of approximately 41 percent over the human worker, plus relieving that worker of a dirty and unpleasant work task. These same tests also indicated the robot produced slightly better quality of work (in terms of variance in coating thickness) than the skilled human worker.

It should be noted that this robot and its associated systems provide the basic framework for robotic application of other interior spraying tasks. As an example, this robot could be easily modified and reprogrammed to perform interior spray painting, plastering, or acoustical ceiling applications. Different operations would obviously require reprogramming, but may also require new and/or additional sensory equipment for navigation and quality control.

### 6.3.2 Painting Robot

In Europe, the SOFFITO robot was developed for painting ceilings. This robot physically resembles the Shimizu SSR-3, but is capable of autonomous operation and movement. The robot's movement is controlled with navigation software which plans the robot's path through the work area. A belt of 24 ultrasonic sensors about the robot's periphery (19-403) provide distance information to the controller, from which the controller can calculate the robot's position in the work area.

At present, this robot is not capable of painting and moving at the same time. The manipulator arm is programmed to paint an area of .9 meter by 1.6 meters (approximately 3 feet by 5.25 feet) (19-403). After painting an area, the robot moves to the next area, continuing this sequence until the entire programmed surface has been painted.

### 6.3.3 Wall Board Robots

Another type of interior finishing activity is the installation of boards on walls, partitions, and ceilings. Two robots are currently used to perform these tasks: the BM.02 (developed by the Taisei Corporation) and the CFR-1 (developed by the Shimizu Corporation).

#### 6.3.3.1 Taisei Wall Board Robot (BM.02)

The BM.02 robot (see Figure 27 for a schematic diagram and Table 8 for specifications) is designed to install large and heavy boards on walls and partitions. This robot is manually controlled, with the robot lifting and supporting the wall board in place while a worker attaches the board to the supporting frame. The robot utilizes vacuum suction pads to grasp and hold the board. The optional cart allows storage and movement of 5 to 8 wall boards with the robot, further reducing installation time. With this robot, only one workman is required to complete this operation; manual installation of wall board normally requires two or more men.

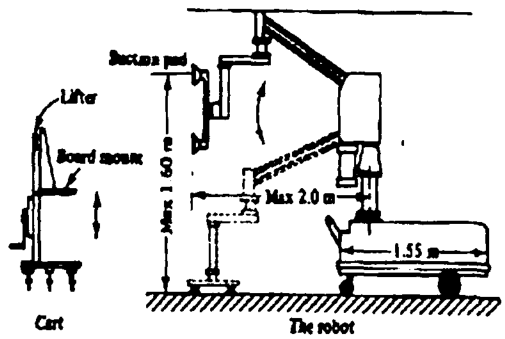



Figure 27 - Taisei BM.02 Robot

Source: Ref. #8 - Industrialization and Robotics in Building: A Managerial Approach

| | Efficiency | Dimensions & Weight |
|---|---|---|
| Setter<br>Mobile with suction pads | Traveling speed: 30 m/min | Height 1950 (1750) mm |
| | Manipulator's capacity | Width: [illegible] mm |
| | | Length: [illegible] mm |
| | Slewing radius 800 ~ 2000mm | Weight [illegible] kg |
| | Vertical lift 0 ~ 1800mm | |
| | Power: Traveling DC12V, [illegible]W<br>Sucking AC100V, [illegible]W | The values in parentheses are the minimum for storage |
| Cart special | Loading capacity: 400 kg | Height: [illegible] mm |
| | Winch box | Width: 700 mm |
| | Wire take-up automatic braking type | Length: [illegible] mm |
| | | Weight: 120 kg |

Table 8 - Taisei BM.02 Specifications

Source: Ref. #20 - Wall Board Manipulator

6.3.3.2 Shimizu Ceiling Panel Robot (CFR-1)

The CFR-1 robot (see Figure 28 for a schematic diagram and Table 9 for specifications) is designed to install lighter boards on ceilings. At the beginning of operations, the robot is placed immediately below the location where the first panel is to be installed. The robot lifts the first panel into place; exact alignment is not necessary, since the robot automatically adjusts the position of the panel to abut adjacent structures and/or panels. After a worker

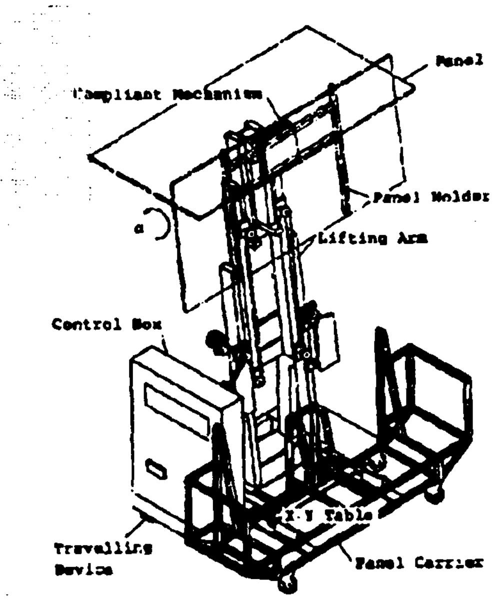



Figure 28 - Shimizu CFR-1 Robot

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

| | |
|---|---|
| Robot | Dimensions L1300, W700, H1750 mm<br>Weight 300 kg<br>Travel speed 3 m/min (working)<br>30 m/min (trasporting) |
| Manipulator (X-Y Table) | Degrees of freedom 4<br>Motion range X axis 300 mm<br>Y axis 150 mm<br>Z axis 1500 mm<br>θ axis 90° |
| Panel carrier | Dimensions L1900, W500, H1000 mm<br>Weight 50 kg<br>Carrying capacity 20 panels |
| Others | Power source AC100V, 50/60Hz<br>Panel size L1820, W910, T12 mm |
| Work Capacity | 25 panels/hour |

Table 9 - Shimizu CFR-1 Robot Specifications

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

fastens the panel in place, the robot automatically advances one panel length for installation of the next ceiling panel. The use of the CFR-1 robot eliminates the need for scaffolding, reduces the labor requirement to one man (as opposed to two or more men required for manual operations), relieves the human worker of repetitive lifting and holding ceiling panels overhead, and increases productivity. On-site applications have confirmed an increase of approximately 50 percent over manual installation (14-282).

### 6.3.4 Interior Partition Robots

In 1988, researchers at the Massachusetts Institute of Technology developed two robots, the Trackbot and the Studbot (collectively called the Wallbots), to install straight sections of partition wall framing in large work areas. These robots construct the partition wall framing with steel framing members. Both robots work in tandem to complete this work activity.

The Trackbot installs stud wall tracks along the floor and ceiling. The robot is guided by a rotating laser beam; the laser is placed at the end of the wall, projecting the laser beam along the floor and ceiling. The Trackbot uses photodetectors to follow this laser line while installing floor and ceiling tracks. The Trackbot is capable of carrying ten 10 foot sections of track in its storage bin. When the Trackbot reaches a location to install a track, vacuum grippers grip and place the track, which is then fastened in place with nail guns.

The Studbot follows the Trackbot and installs the steel studs in the floor and ceiling tracks. Before starting, the floor plan is programmed into the Studbot's controller, providing location information for each stud that will be installed. The Studbot rolls along the floor track, using the track for guidance. When it reaches a location for the installation of a stud, the Studbot handling arm grips the top stud in the storage bin with vacuum grippers, passing the stud to the installation arm. The installation arm swings the stud upright and places it between the floor and ceiling tracks. After the stud has been properly located, crimping tools at the end of the installation arm pierce the stud and track, locking the stud in place; installation is completed without screws or other mechanical fasteners. The Studbot has a storage capacity of 100 studs in its storage bin.

As demonstrated by the above discussion, the Wallbots have fully automated the construction of interior partition wall framing. To date, though, there is no evidence of actual use in a construction project.

## 6.4 FLOOR FINISHING ROBOT

Section 5.4.2.3 discussed the capabilities of the floor finishing robot. In general, this type of robot has relatively limited diversity in use and operation, but utilizes more sophisticated navigation software and sensor/controller interface than other generic robot families.

### 6.4.1 Concrete Screed Robots

Concrete screed robots are designed to screed and level concrete after placement and prior to finishing. Automation of this operation relieves human workers of physically tiring and messy work. Two types of robot screeds have been developed: the Somero 240 Laser Screed and the Takenaka Floor Screeding Robot.

#### 6.4.1.1 Somero 240 Laser Screed

The Somero 240 Laser Screed is a vehicle with a vibratory screed mounted on a telescoping boom; it resembles a bucket truck with the screed replacing the bucket. This robot is used to place and screed concrete to meet tight tolerances of flatness and levelness. In operation, the boom is extended over the concrete slab, with the boom (and screed) slowly retracted toward the vehicle. Concrete is placed with an auger, while lasers check the position of the auger and screed. In 1988, this robot was listed at $165,000 or could be rented at $.10 per square foot (21-26).

#### 6.4.1.2 Takenaka Floor Screed Robot

The Takenaka Floor Screeding Robot is also used for levelling and screeding fresh concrete. The vehicle moves over fresh concrete on four wire cage wheels, using an auger (located between the wheels) to level the concrete and two vibratory screeds (located immediately in front and behind the vehicle) for screeding. Although no information was available regarding the control of this robot, it appears this robot is remotely controlled. Figures 29 and 30 are pictures of this robot in operation.

Figure 29 - Takenaka Concrete Floor Screeding Robot

Source: Ref. #1 - Robotics in Service

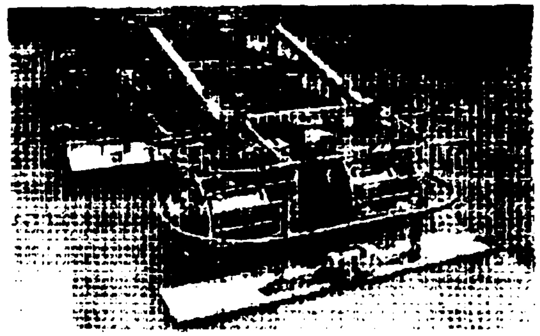


Figure 30 - Takenaka Concrete Floor Screeding Robot

Source: Ref. #17 - Robots - Automation of Construction

### 6.4.2 Concrete Finishing Robots

Concrete finishing appears to be a construction activity that has attracted intense interest in robotization. In general, this type of work requires human workers to maintain an uncomfortable work posture for long periods of time. In addition, this work must be performed when dictated by the conditions of the concrete after placement. In many instances, this work is performed late in the day, often into overtime, after an exhausting day of placing and screeding the concrete. Several different types of robots have been developed to perform this work, cutting production time and labor requirements, and allowing this work to be performed late in the work day or at night without excessive overtime costs or work impact.

### 6.4.2.1 Shimizu FLATKN Robot

The Shimizu FLATKN robot is a round robotic vehicle consisting of travel rollers, power trowels, a controller, and a guard frame. Figure 31 is a schematic diagram and Table 10 lists the specifications for the FLATKN robot. The travel rollers provide the robot with mobility, allowing the robot to move forward, backwards, left, or right. The power trowel mechanism consists of three arms, each arm having three rotating trowels at the end. The angle of the trowels (with respect to the concrete surface) may be adjusted to regulate the quality of the finished concrete surface. In operation, each set of trowels rotates about its trowel arm, with the entire trowel mechanism

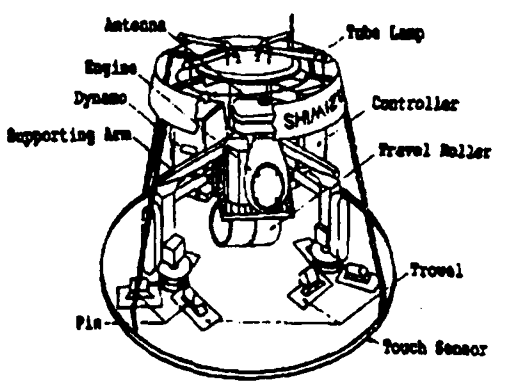



Figure 31 - Shimizu FLATKN Robot

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

| | | |
|---|---|---|
| Dimensions | maximum diameter | 2300 mm |
| | height | 810 mm |
| Weight | 300 kg | |
| Travel speed | 0 to 10 m/min | |
| Trowel | Blade size | L290, W130 mm |
| | Rotating speed | 70 to 100 rpm |
| | Revolving speed | 0 to 13 rpm |
| | Blade angle | 0 to 10 deg. |
| Power source | Trowel | 5.5 PS engine |
| | Travelling device and Controller | 530 VA dynamo |
| Control | By radio remote control (FM, 9ch)<br>- moving back and forth<br>- left or right turning<br>- left or right correction<br>- trowel rotating speed control<br>- travel speed control | |
| Work Capacity | 400 to 800 $m^2/h$ | |

Table 10 - Shimizu FLATKN Robot Specifications

Source: Ref. #14 - Proceedings of the 5th International Symposium on Robotics in Construction

rotating about the central axis of the robot. A gasoline engine powers the trowel mechanism; a separate gasoline generator provides electrical power for the robot, eliminating the need for power cables and increasing the robot's mobility. The FLATKN robot is remotely controlled (by radio), but has touch sensors mounted on its guard ring for collision avoidance.

During its first operational use, the FLATKN robot and two operators finished almost 700 square meters (approximately 7500 square feet) of concrete in one day (14-281). This productivity rate is approximately four to five times that of manual concrete finishing.

6.4.2.2 Kajima Mark II Robot

The Mark II robot consists of a travel unit, double trowel arms mounted on the end of the travel unit, and a bumper unit. Figures 32 and 33 present schematic diagrams of this robot, and Table 11 presents its specifications. Each of the three units may be separated for ease in cleaning and transporting. The robot is electrically powered, with electrical power provided by an external power source through a power cable.

Mobility for this robot is provided by two travel wheels, one mounted on each side of the robot. The robot is capable of forward and backward motion, and

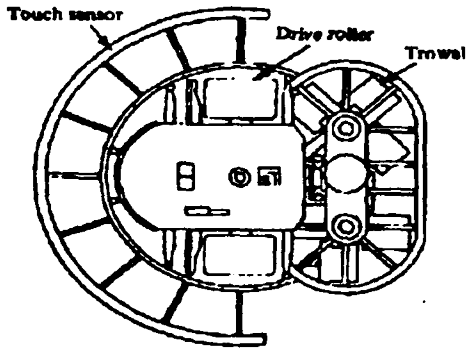



Figure 32 - Kajima Mark II Robot

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

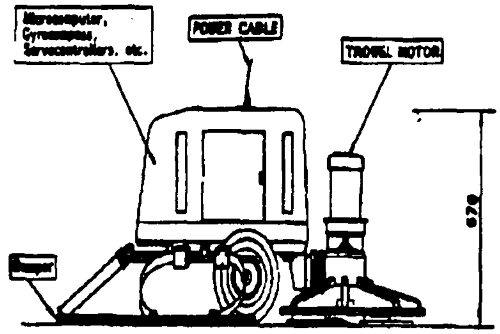



Figure 33 - Kajima Mark II Robot; Side View

Source: Ref. #22 - Proceedings of the 5th International Symposium on Robotics in Construction

turning in the same spot. The robot may be either remotely or automatically controlled. In automatic control, the robot utilizes a self-navigation system consisting of a gyrocompass, measuring rollers, and a microcomputer. For autonomous operation, the robot is programmed with the length and width of the floor area, the operating conditions of the robot (robot travel speed, trowel lapping widths, and direction of robot movement), and the robot's starting point. Obstacles in the work area are detected through the use of touch sensors mounted around the front of the robot; when touched, the robot maneuvers around the obstacle and continues operation.

Each trowel arm has three trowels mounted on the end of the arm. Electric motors rotate each trowel arm

| Items | | Description | |
|---|---|---|---|
| Size (mm, excluding bumper) | | 1,600 (L) x 1,200 (W) x 670 (H) | |
| Weight (kg) | Travel device | 106 | Total: 186 (Dividable into three units by one touch of a button) |
| | Trowel | 75 | |
| | Bumper | 5 | |
| Travel Speed | | 0 - 230 mm/sec. | |
| Finishing Capacity | | 300 $m^2$/hour x 3 times finishing (depends on concrete spec. weather) | |
| Drive System | Automatic | After predetermining the working area, merely touching a button will be enough to start | |
| | Remote Control | Start and stop, forward and backward movement rotation can be radio controlled | |
| Control System | | Independent automation control system with microcomputer gyrocompass, and travel distance sensor | |
| Power Supply | | 200 VAC, 3 phase, 1.5 KVA | |
| Safety Devices | Obstacle avoidance | Touch sensor (avoiding drive bumper, travel device stops) | |
| | Opening detector | Laser sensor (stop) | |
| | Infilling detector | Touch sensor (stop when concrete is flabby) | |
| | Alarm device | Flashing light (white while moving, red in an emergency) | |

Table 11 - Kajima Mark II Robot Specifications

Source: Ref. #22 - Proceedings of the 5th International Symposium on Robotics in Construction

in opposite directions, offsetting reaction forces and allowing the robot to travel straight. During operation, the Mark II robot is capable of the same production rates as the FLATKN robot, but the production rate is dependent upon the programmed robot speed and trowel overlap. In terms of surface quality, the Mark II robot produces a surface flatness and smoothness that is slightly better than manual methods.

6.4.2.3 Takenaka SURF ROBO

Figure 34 is a schematic diagram of the SURF ROBO and Table 12 lists the robot's specifications. The

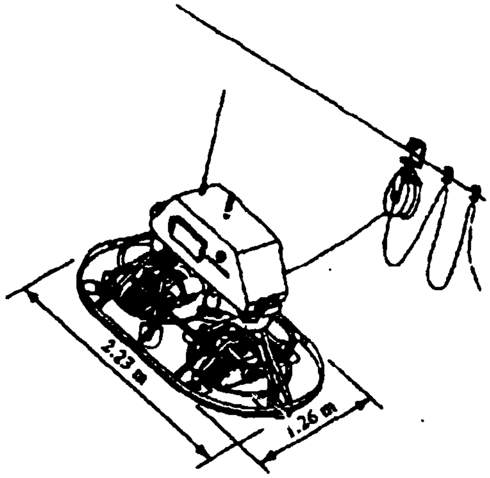



Figure 34 - Takenaka SURF ROBO

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

| Model | TSCP-2000 |
|---|---|
| Measurement (L×W×H) | 2230×1260×1350mm |
| Weight | 185 kg |
| Contact Pressure at Trowelling | 0.12 kg/cm² |
| Finishing Work Capability | 300 m²/H (at two step finishing) |
| Standard Run Way Width for Finishing | 2140 mm |
| Rotation Speed of Blades | 0~85 r.p.m |
| Travelling Speed | 0~12 m/min |
| Operation | Radio Control and Microprocessor Control |

Table 12 - Takenaka SURF ROBO Specifications

Source: Ref. #23 - Proceedings of the 5th International Symposium on Robotics in Construction

SURF ROBO consists of two trowel arms, two tracked drive units, and the controller. The robot is electrically powered; electrical power is provide by an external power source through a power cable. Before operation, a messenger cable is installed along the centerline of the work area to facilitate handling of the external power cable.

Each of the trowel arms has four trowels attached to its end, with each trowel arm rotating in opposite directions during operation. The quality of the finished concrete surface is controlled by the following factors: trowel blade angle, trowel arm rotation speed, and trowel pressure. The trowel blade angle (with respect to the surface of the concrete) can be adjusted to three different positions, up to a maximum of 10 degrees. The trowel arm rotation speed is adjustable from 0 to 35 rpm. Sensors on the trowel arms detect the trowel arm pressure, allowing this pressure to be adjusted by the control unit.

Mobility is provided by two independently controlled tracked drive units. The robot may move forward or backward, and turning is accomplished by lifting the trowel arms off the concrete surface and turning the robot (minimizing "peeling" of the concrete surface). The robot may be either remotely or automatically controlled. Prior to autonomous operation, the dimensions of the work area are entered into the robot controller, with the robot controller calculating and controlling the robot's path. Touch sensors installed around the guard ring permit collision avoidance. It should be noted that the robot is "tied" to the messenger cable, limiting its mobility in the work area and around obstacles.

During operation, the SURF ROBO has demonstrated a productivity rate of approximately 300 square meters (approximately 3250 square feet) per hour, with a daily production of 1200 to 1500 square meters (approximately 13,000 to 16,000 square feet) (23-564). Labor crews were reduced by one-half, and the concrete finish exceeded that of manual methods.

6.4.2.4 Ohbayashi Floor Trowelling Robot

The Ohbayashi Floor Trowelling Robot is a self-contained vehicle, physically similar to the Kajima Mark II robot. As with the other robots in this class, this robot is capable of movement in any direction. This robot may be either remotely or automatically controlled, with automatic control being the normal mode of operation. Figure 35 presents a schematic diagram and Table 13 lists the specifications for this robot.

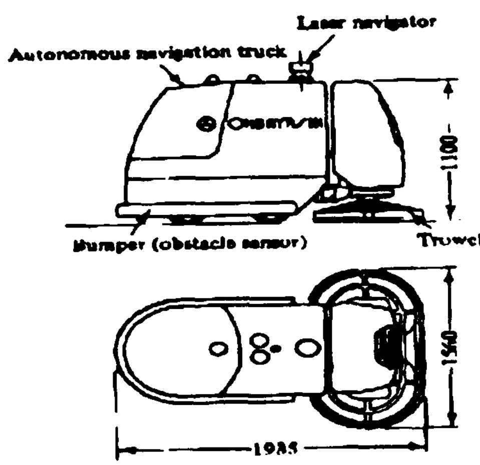



Figure 35 - Ohbayashi Floor Trowelling Robot

Source: Ref. #8 - Industrialization and Robotics in Building: A Managerial Approach

| | |
|---|---|
| Composition | Autonomous navigation truck, twin trowel |
| Performance | Finishing capacity : av. approx. 500 m²/hr |
| | Travelling speed : 0 - 10 m / min |
| | Continuous operating time : 4 hr or longer |
| Control | Wireless manual control, full - automatic |
| Sensor | Opening and obstacle sensor |
| Motive power supply | Engine generator mounted |
| Outside dimensions | (Width) 1540 x (length) 1985 x (height) 1100 mm |

Table 13 - Ohbayashi Floor Trowelling Robot Specifications

Source: Ref. #24 - Proceedings of the 5th International Symposium on Robotics in Construction

The outstanding feature which distinguishes this robot from the other robots of this class is its navigation system: this robot utilizes lasers for position determination and subsequent movement control by the controller. Before operation, four laser reflectors are installed outside the work area, preferably near the corners. The robot incorporates a laser transmitter and receiver; the robot continuously transmits a rotating horizontal laser beam and measures the angle to each reflector, triangulating the robot's position within the work area. During operation, three reflectors should be "visible" at any one time. If three angles are not obtained due to obstructions, the robot continues on its current path utilizing linear sensors and translators until three reflectors are again visible. This navigation system provides a position accuracy of +/- 5 centimeters (approximately 2 inches) and a heading accuracy of +/- .5 degrees (25-323). As with the other robots of this class, touch sensors installed on a guard ring permit collision avoidance with obstacles.

6.4.3 Floor Finishing Robot

The Shimizu Corporation has developed a robot, called the Multi-purpose Travelling Vehicle (MTV-1), for grinding and cleaning floors. The robot consists of two sections;

the first section contains the robot control and drive unit, while the second section is an end effector module that may be changed to perform different tasks (currently grinding or cleaning). Figures 36 and 37 are schematic diagrams of the MTV-1 robot, showing both end effectors.

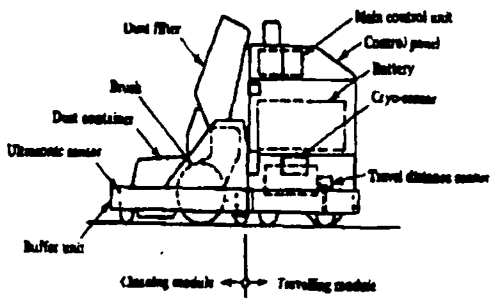



Figure 36 - Shimizu MTV-1 Robot with Cleaning Module

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

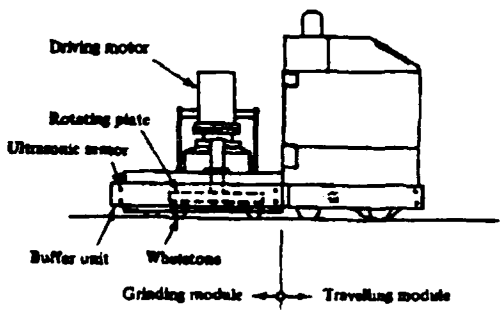



Figure 37 - Shimizu MTV-1 Robot with Grinding Module

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

The robot control and drive module is a self-contained unit. The robot is powered by electricity, through batteries stored in the control and drive module. The robot performs its work function autonomously, without the requirement for operator input prior to starting operation. During operation, the robot first moves about the work area perimeter, mapping the work area boundaries. After tracing the work area, the robot utilizes an onboard directional sensing device (gyro-sensor) to plan its path. Ultrasonic sensors are used for collision avoidance.

As stated above, the robot has interchangeable end effectors for the performance of simple and repetitive floor finishing work. The cleaning module uses a brush for cleaning, while the grinding module uses a whetstone for grinding. With the development of additional floor finishing modules, this robot will be capable of additional work tasks.

## 6.5 EXTERIOR WALL FINISHING ROBOTS

As previously discussed in section 5.4.2.4, exterior wall finishing robots are used to finish large vertical surfaces, both interior and exterior. In general, this type of robot is suspended from the roof or ceiling with cables or ropes. Current technology allows this type of robot to perform a variety of tasks.

### 6.5.1 Spray Application Robots

This class of robots is designed to apply different types of coating materials on vertical surfaces. This class of robots utilizes spray guns to apply the coating materials to the vertical surface. The most common application for this class of robot is painting of walls. The robot vehicle houses and maneuvers the spray gun over the surface, with the coating material and compressed air (if necessary) provided from either the roof or the ground.

6.5.1.1 <u>Shimizu SB-Multicoater Robot</u>

The Shimizu SB-Multicoater robot is designed to apply different types of coating materials to vertical surfaces. The robot consists of two sections: the trolley, which rides along a rail installed along the top of the wall; and the robot carriage, which is suspended from the trolley. Figure 38 presents a schematic diagram of this robot.

The robot may be either remotely or automatically controlled. Prior to autonomous operation, the controller must be preprogrammed with the work and robot movement sequence. This robot is capable of coating 300-400 square meters (approximately 3250-4350 square feet) per day (8-392). This application rate is four to five times faster than manual applications.

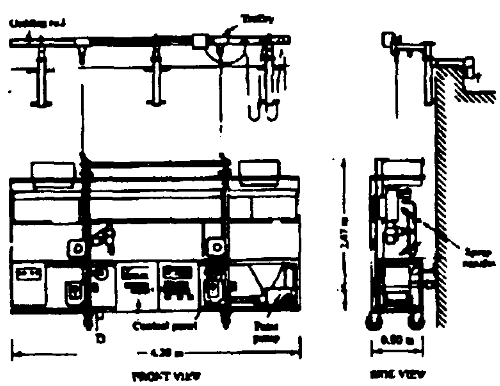



Figure 38 - Shimizu SB-Multicoater Robot

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

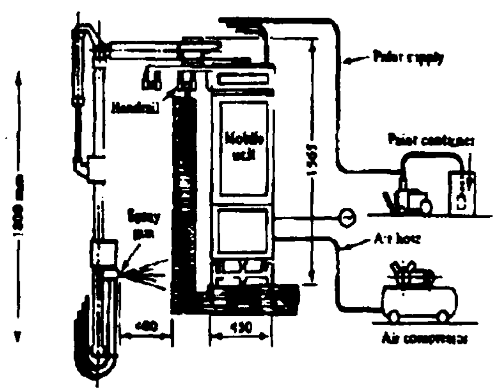



Figure 39 - Shimizu OSR-1 Robot

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

#### 6.5.1.2 Shimizu OSR-1 Robot

The Shimizu OSR-1 robot was developed to paint balustrades for high-rise residential and commercial buildings. The spray gun is attached to an arm that is hung over the balustrade; the main robot unit (controller and travelling device) is located inside the balustrade. Refer to Figure 39 for a schematic diagram.

The robot may be either manually or automatically controlled. Prior to autonomous operation, the robot is preprogrammed with the work sequence. During operation, the robot vehicle moves along the balustrade, with the spray gun moving up and down the arm. Touch sensors allow the robot to avoid objects abutting or protruding through the balustrade.

#### 6.5.1.3 Taisei Painting Robot

The Taisei Painting Robot was designed to paint vertical surfaces, both textured and smooth finishes, with automatic detection and avoidance of windows. The robot consists of two sections: the robot section, which paints the wall surface; and the roof-car section, which controls the vertical and lateral movement of the robot section. Figure 40 is a drawing of this robot system and Table 14 lists the robot's specifications.

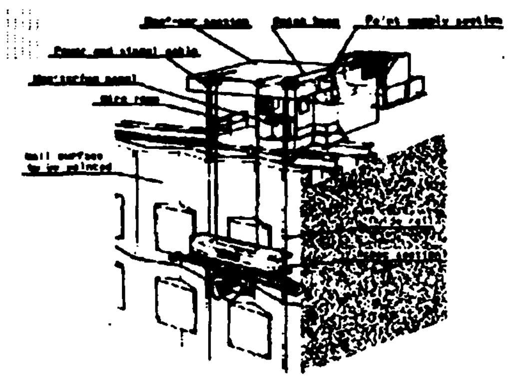


Figure 40 - Taisei Painting Robot

Source: Ref. #26 - Proceedings of the 5th International Symposium on Robotics in Construction

| | Item | Specifications |
|---|---|---|
| [illegible] | Roof car | Lifting load: 1.5 tons<br>Descending speed: [illegible] m/min<br>Ascending speed: 36 m/min<br>Power consumption: 7.6 kW ([illegible]) ([illegible]) |
| | Painting devices<br>Paint tanks<br>Paint pump<br>Compressor | Power consumption: 7.5 kW ([illegible])<br>[illegible]-liter x 2<br>12 liters/min max.<br>[illegible] HP |
| Robot Section | Overall dimensions | [illegible] x 1.0m x 2.0m ([illegible])<br>Power consumption: 6 kW ([illegible]) |
| | Weight | 1.5 tons |
| | Devices<br>Compressor<br>Control devices | <br>2.2 kW ([illegible])<br>Programmable controller (for [illegible] control)<br>Up/down movement distance sensor<br>Wall joint sensor<br>Wall surface sensor |
| | Safety devices | Automatic release of carrier lock<br>Receptacle for emergency power supply |
| | Hood<br>Painting capability<br>Spray guns | [illegible] x 600 mm ([illegible])<br>300 m²/h<br>8 airless-type guns |

Table 14 - Taisei Painting Robot Specifications

Source: Ref. #26 - Proceedings of the 5th International Symposium on Robotics in Construction

The robot section contains the paint hood, a rail allowing lateral movement of the paint hood, various motors for positioning the control hood, and a control panel for controlling the movement and position of the paint hood; refer to Figure 41 for a schematic diagram of the robot section. The paint hood contains eight spray guns, mounted in pairs and at different angles, minimizing the drifting of paint mist and allowing complete coverage of the wall surface. The paint hood has mounted sensors for detecting the wall surface, detecting windows (to prevent paint over-spray onto the window), detecting the angle of the wall (allowing the

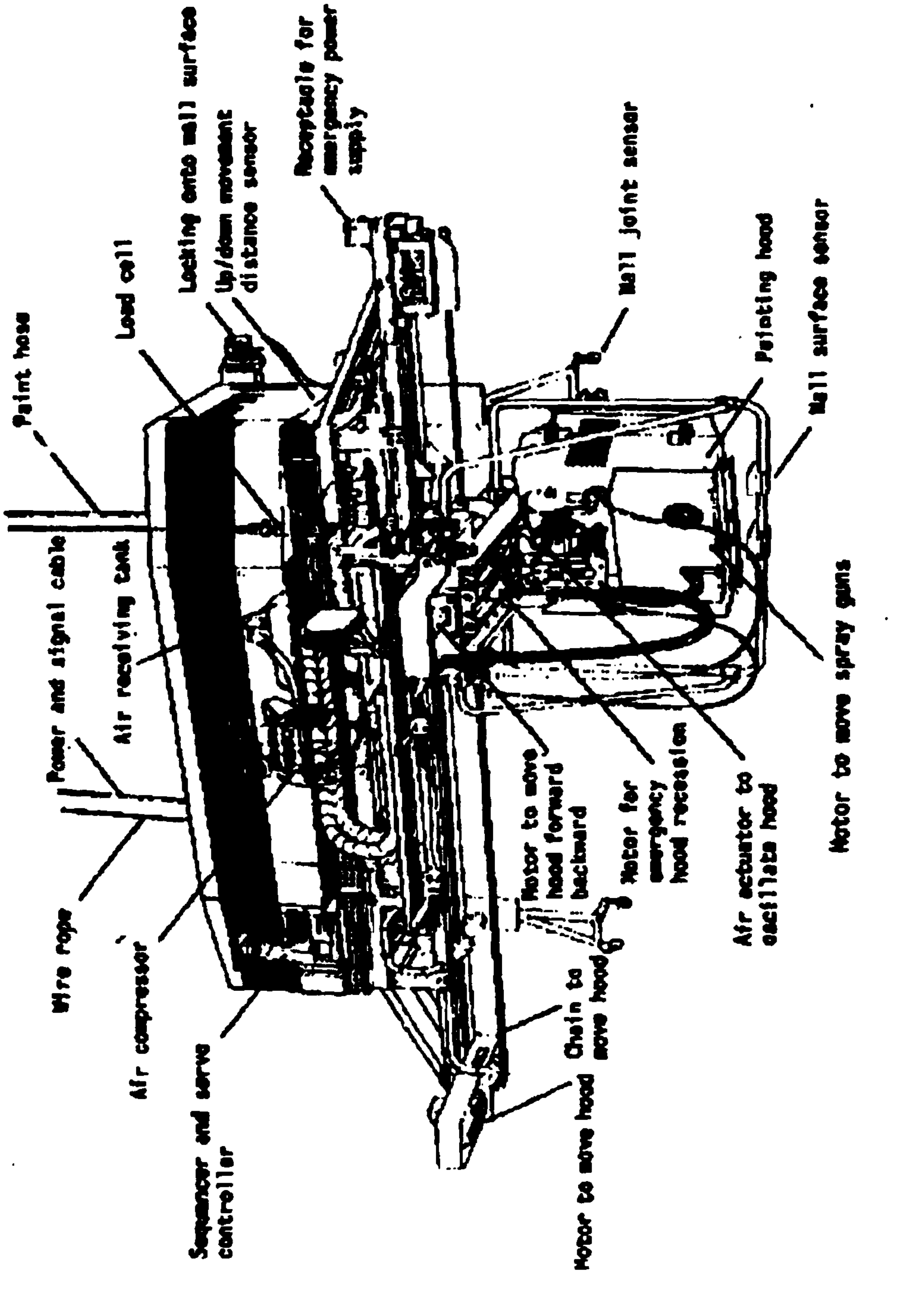



Figure 41 - Taisei Painting Robot; Robot Section Details

Source: Ref. #26 - Proceedings of the 5th International Symposium on Robotics in Construction

paint hood to be positioned parallel to the wall), and detecting wall panel joints (for determining the hood location). The robot section is automatically controlled, using information from the hood sensors for movement and spray gun control.

During operation, the robot determines its position, then stops at a programmed location. Once in position, the paint hood moves into close contact with the wall surface and the spray guns begin painting. The spray guns inside the paint hood move back and forth, painting an area of 4500 square centimeters (approximately 5 square feet) (26-415). After painting this location, the paint hood moves away from the wall and is moved to a new location. This sequence is continued until painting has been completed.

#### 6.5.1.4 Kumagai-gumi Wall Climbing Robot

The Kumagai-gumi Corporation of Japan has developed a wall climbing robot that is capable of multi-functional vertical work tasks. At present, this robot system is capable of performing painting and shot-blasting of vertical surfaces. The robot system consists of the following units: the wall climbing robot, the shot-blasting unit, and the painting unit.

The wall climbing robot is designed to move freely on a vertical surface, maneuvering a work unit about the surface. The wall climbing robot uses a suction force (produced by a vacuum unit located on the ground) to hold the robot to the wall surface, eliminating the need for suspension cables and trolley rails for robot movement; suspension cables are still required to prevent the robot falling in the event it detaches from the wall. The wall climbing robot is capable of moving at 5 meters per minute (approximately 16.5 feet per minute) (27-422).

The shot-blasting and painting units attach directly to the wall climbing robot. During shot-blasting or painting operations, the robot may be either remotely or automatically controlled. Under automatic control, various sensors detect and measure the robot's position and attitude (with respect with the wall surface). The supply of paint and shot-blasting materials is provided by pumps from sources located on the ground.

### 6.5.2 Exterior Wall Inspection Robots

Exterior wall inspection robots are relatively small and lightweight robots used to detect voids or other defects in the attachment of exterior wall panels to the building structure. The robots move about the surface of the wall, either suspended from overhead by cables or through the use of vacuum grippers. Movement is generally accomplished under autonomous control, with onboard sensors for the detection of obstacles and openings. In general, the robot inspects the wall by either tapping the surface or using ultrasonic sensors. When defects are detected, the location of the tile is entered into computer memory for subsequent review and repair. Figure 42 is a drawing of the Kajima Tile Inspection Robot, which is representative of other wall inspection robot systems manufactured by the Takenaka Corporation, the Taisei Corporation, and the Ohbayashi Corporation.

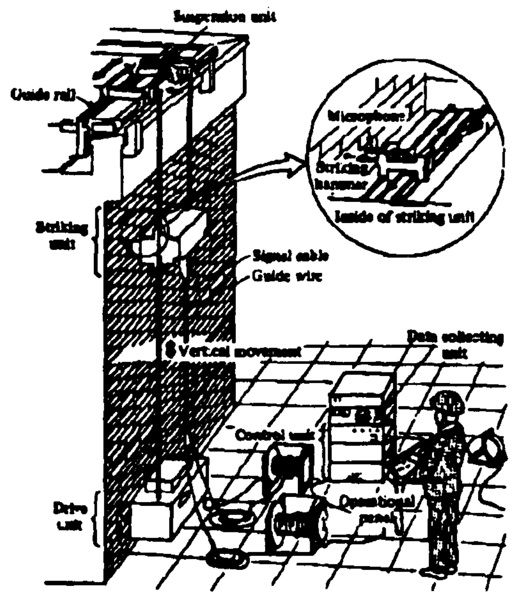



Figure 42 - Kajima Tile Inspection Robot

Source: Ref. #8 - <u>Industrialization and Robotics in Building: A Managerial Approach</u>

## 6.6 OTHER CIVIL ENGINEERING ROBOTS

In addition to the building construction robots discussed above, other robots have been designed to perform other civil engineering applications. Examples include robots for cutting concrete and pavement, tunnelling, shotcreting, nuclear reactor decontamination and deactivation, materials handling, concrete cutting, pipe inspection, leak detection, and others. Recent advances have also allowed the automation of various aspects of excavation work (such as laser guided blade control for scrapers and graders), with complete automation possible in the near future.

## 6.7 WHERE ARE THE CONSTRUCTION ROBOTS?

Tables 15 and 16 summarize the research and development efforts in construction robots. Note that these tables do not list all construction robots; several robots which have been discussed in this paper are not listed in these tables. In a direct comparison, it would appear that the United States has maintained its "share" of construction robot research and development, and this is true. Robotic research development is active at U.S. research institutions and universities, such as MIT and Carnegie Mellon University.

What these tables do not reveal is the actual implementation of construction robots after research and

| System Description | Application | Research Center |
|---|---|---|
| John Deere 690C | tele-operated excavation machine | John Deere, Inc., Moline, IL |
| Laser-Aided Grading System | automatic grading control for earthwork | Gradeway Const. Co. & Agtek Development Co., San Francisco, CA; Spectra-Physics, Dayton, OH |
| Automatic Slipform Machines | placement of concrete sidewalks, curbs, and gutters | Miller Formless Systems Co., McHenry, IL; Gomaco, Ida Grove, IA |
| Micro-Tunnelling Machine | tele-operated micro-tunnelling | American Augers, Wooster, OH |
| Robotic Excavator (REX) | autonomous excavation, sandblasting, spray washing, & wall finishing | The Robotics Institute, Carnegie Mellon Univ., Pittsburg, PA |
| Terregator | autonomous navigation | The Robotics Institute, Carnegie Mellon Univ., Pittsburg, PA |
| Remote Core Sampler (RCS) | concrete core sampling for radiated settings | The Robotics Institute, Carnegie Mellon Univ., Pittsburg, PA |
| Remote Work Vehicle (RWV) | nuclear accident recovery work, wash contaminated surfaces, remove sediments, demolish radiation sources, apply surface treatment, package & transport materials | The Robotics Institute, Carnegie Mellon Univ., Pittsburg, PA |
| Wallbots | construction of interior partitions, metal track studs | Massachusetts Institute of Technology, Cambridge, MA |
| Blockbots | construction of concrete masonry walls | Massachusetts Institute of Technology, Cambridge, MA |
| Shear Stud Welder | weld shear connectors in composite steel/concrete construction | Massachusetts Institute of Technology, Cambridge, MA |
| Automated Pipe Construction | pipe bending, pipe manipulation, & pipe welding | University of Texas at Austin, TX |

Table 15 - Construction Robot Research and Development in the United States

Source: Ref. #28 - "New Technology Coming to Construction"

development. Development and implementation are two distinctly separate activities; new technologies and capabilities are actively researched and developed, but the U.S. research institutions lack the ability to market their robotic developments. In contrast, the Japanese ultimately place their robotic developments in use. In Japan, most of the robotic research and development is undertaken by private firms (with limited assistance by the Japanese

| System Description | Application | Research Center |
|---|---|---|
| | (a) Concrete | |
| Shotcrete Robot | Spray concrete for tunnel liner | Kajima Co. & Ohbayashi Co., Japan |
| Slab-Finishing Robot | Finish surface of cast-in-place concrete | Kajima Co., Japan |
| Automatic Laser Beam-Guided Floor Robot | Finish surface of cast-in-place concrete | Ohbayashi Co., Japan |
| Horizontal Concrete Distributor (HCD) | Place concrete for horizontal slabs | Takenaka Komuten Co., Japan |
| Automatic Concrete Vibrator/Tamper | Vibrate cast-in-place concrete | Ohbayashi Co., Japan |
| Automatic Concrete Distribution System | Carry concrete from batching plant to the cable crane | Ohbayashi Co., Japan |
| Concrete Placing Robot for Slurry Walls | Place and withdraw tremie pipes and sense upper level of concrete as it is poured | Ohbayashi Co., Japan |
| | (b) Non-concrete Spraying | |
| Fireproof Spraying Robot | Fireproof structural steel | Shimizu Co., Japan |
| Paint Spraying Robot | Paint balcony rails in high-rise buildings | Shimizu Co., Japan |
| | (c) Structural Members | |
| Auto-Clam Auto-Clamp | Erect structural steel beams and columns | Ohbayashi Co., Japan |
| Structural Element Placement | Place reinforcing steel | Kajima Co., Japan |
| Automatic Carbon Fiber Wrapper | Wrap existing structures with carbon steel | Ohbayashi Co., Japan |
| Structural Element Welding | Weld large structural blocks for cranes and bridges | Mitsubishi Heavy Industries Co., Japan |
| | (d) Inspection | |
| Wall Inspection Robot (KABEDOMBA) | Inspect reinforced concrete walls | Ohbayashi Co., Japan |
| Wall Inspection Robot | Inspect facade | Kajima Co., Shimizu Co., & Taisei Co., Japan |
| Bridge Inspection Robot | Inspect structural surface of bridges | University of Wales, U.K. |
| GSD Robot | Finish facade/surface | Eurosa, France |
| | (e) Tunnelling | |
| Shield Machine Control System | Collect and analyze data for controlling tunnelling machine | Ohbayashi Co., Japan |
| | (f) Excavation | |
| Super Hydrofraise Excavation Control System | Excavate earth | Ohbayashi Co., Japan |
| Tunnel Wall Lining Robot | Assemble wall liner segments in tunnels for sewer systems and power cables | Ishikawajima-Harima Heavy Industries; Tokyo Electric Power Co.; Kajima Co., Japan |
| | (g) Other | |
| Clean Room Inspection and Monitoring Robot (CRIMRO) | Inspect and monitor the amount of particles in the air | Ohbayashi Co., Japan |
| Integrated Surface Patcher | Hot resurfacing on highways | Secmar Co., France |
| Material Handling | Pick-up and distribute construction materials, e.g., prefabricated concrete materials and pipe | Tokyo Const. Co. Ltd., and Hitachi Const. Co. Ltd., Japan |

Table 16 - Construction Robot Research and Development Outside the United States

Source: Ref. #28 - "New Technology Coming to Construction" government), who immediately put these new products (robots) to work.

Tables 15 and 16 further illustrate the diversity of robots available for building construction use. But in terms of actual implementation, the United States lags far behind several other countries, notably Japan and Western Europe. In simple terms, construction robots are available for purchase and use, but very few of these robots have been actually used in construction projects in the U.S. Japan and Western Europe lead in the implementation of construction robots for the following reasons:

a. These countries face severe labor shortages, both in skilled (tradesmen) and unskilled workers. To ease this manpower shortage, robots are developed and implemented.

b. These countries, particularly Japan, are not as resistant to change in construction methods, processes, and technology. When new methods, processes, and technology are developed, the Japanese are willing to take risks and try them.

c. These countries, particularly Japan, are more far-sighted in terms of technological developments and growth. Japan conducts its robotic research and development with an eye towards the future, attempting to foresee the future impact new research and development will have on the construction industry and society.

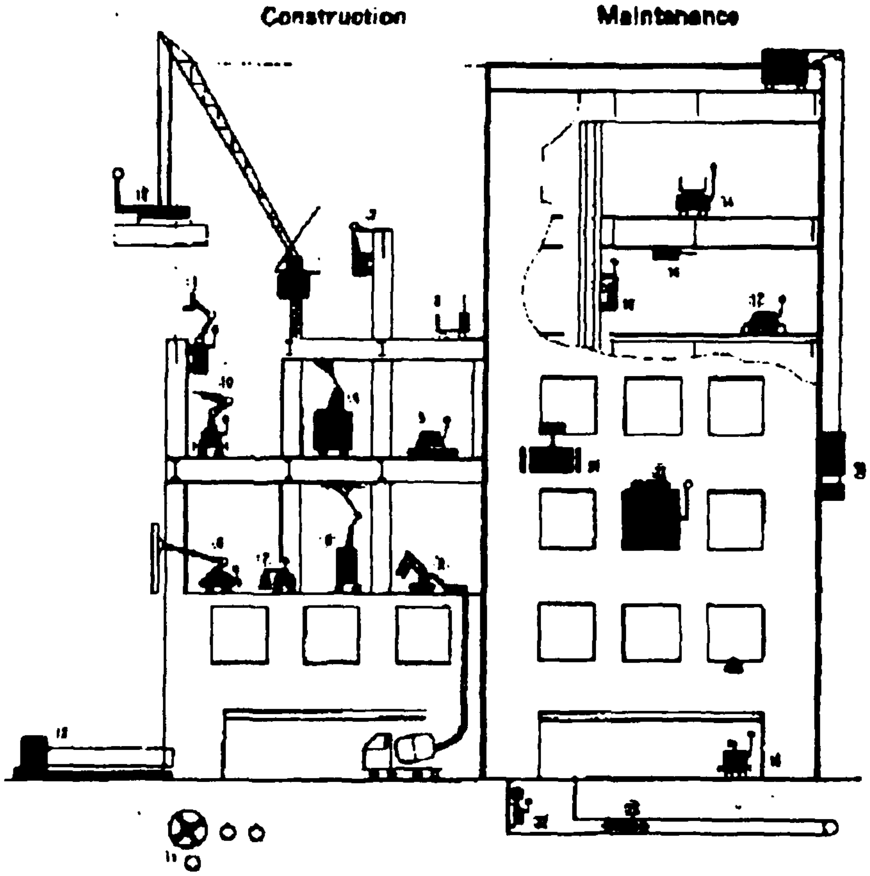
# CHAPTER SEVEN

# CONCLUSION

## 7.1 CONCLUSION

At present, robots see limited use and application in the construction industry. Robots are currently limited to simple, labor intensive tasks, such as concrete work and wall painting. These limitations are due to the limits in robotic technology, but the potential for increased use is immense. Many companies envision "totally" automated construction projects, such as that shown in Figure 43. Research and development efforts continue to produce new ideas and uses for robots in construction, with new developments occurring almost daily. As robotic technology develops, particularly in the areas of artificial intelligence and vision sensor systems, more robots will be developed for performing expanded work and tasks in the construction industry. As such, the use of robots in construction will increase dramatically, with that increase coming about in the near future. In my opinion, we will see a robotics "explosion" in the construction industry in the 1990's.

As noted in Chapter 6, most of the research, development, and implementation of robots in the construction industry has been performed by the Japanese. The Japanese have been using robots in construction since




1 Steel frame erecting robot
2 Steel frame welding/bolt tightening robot
3 Material transport robot
4 Fireproof spraying robot
5 Floor finishing robot
6 Robot to manipulate exterior wall board
7 Floor cleaning robot
8 Robot to manipulate wall board
9 Concrete placing robot
10 Interior finishing robot (spraying, painting)
11 Pipe embedding robot
12 Reinforcement bar erecting robot
13 Position controlling robot
14 Package transport robot
15 Security patrol robot
16 Duct cleaning robot
17 Floor cleaning robot
18 Piping system diagnosing robot
19 Exterior wall maintenance robot (painting, cleaning)
20 Exterior wall diagnosing robot
21 Window cleaning robot
22 Tank cleaning robot
23 Pipe inspection robot (gas, sewage)

Figure 43 - Conceptual Use of Robots in Construction

Source: Ref. #29 - Robot

the mid-1980's. Through their efforts, they have proven that robotics are viable and valuable assets in construction. The Japanese have demonstrated the high productivity, the high quality, the excellent investment potential, and the savings generated by using robots in the construction industry. The Japanese continue to focus resources and attention to the research and development of construction robots, maintaining their lead over the rest of the world.

In the United States, virtually no robots are used in construction. It is not that robots are not available, because the Japanese will market their robots (in the recent past, though, the Japanese have been relatively passive in marketing their construction robots). The biggest obstacle to construction robot implementation in the United States is the attitude of contractors and construction firms. In general, construction contractors are very resistant to change, and the use of robots would be a monumental change in the construction industry.

But, as productivity continues to decline, the workforce continues to get older, and the skills of the workforce continue to deteriorate, change will be necessary. This change may be forthcoming in the very near future, as robot implementation will be required to remain competitive in the construction industry. To date, the Japanese (and other countries possessing construction robots) have not expanded their operations into the international construction market. With the productivity and profitability of robots, though, foreign companies could certainly win bids and perform construction work in the United States, taking work away from domestic firms.

## 7.2 RECOMMENDATIONS

The following recommendations are offered to increase the use of robots in the U. S. construction industry.

### 7.2.1 Large Projects

Due to their increased productivity, robots are more productively employed on large construction projects. Productivity and profitability increases when the robot is used in large, relatively uninterrupted work areas. For instance, the Shimizu FLATKN concrete floor finishing robot would be an excellent tool for finishing large areas of concrete, such as warehouses, shopping malls, large buildings, or large residential housing projects. This robot would not be practical on small, one-time projects, such as the construction of a single residence. The key to this recommendation is that the use of robots may be limited to large or highly specialized construction firms. These firms would be able to purchase a robot and maintain a workload that keeps the robot productively employed.

### 7.2.2 Leadership

The construction industry needs a "leader" to purchase and use construction robots, proving their profitability, productivity, and viability to the rest of the construction industry. The best "leader" would be a construction contractor, whose evaluation would carry the most merit with the rest of the industry. Other "leaders" could include state or federal government entities, such as the military or state universities. These agencies could purchase and test construction robots, ultimately incorporating them in construction projects (as subcontractors for the prime contractor) to verify and/or prove performance in an actual construction project.

### 7.2.3 Research and Development

In Japan, the research and development of construction robots is performed by the companies who will actually use those robots. These construction companies maintain active research and development divisions within the corporate organization, with the corporation funding all research and development activities. Under this arrangement, construction robots are developed to complete specific projects, then modified for general use. As an example, the Taisei wall painting robot (discussed in section 6.5.1.3) was designed to paint the exterior of Shinjuku Center Building in Tokyo (26-412). The exterior skin of this building consisted of angled, rough finished concrete panels. This finish presented various problems for robotic painting; once developed, the Taisei painting robot could be used to paint practically any surface.

In the United States, most of the research and development for construction robots is performed by universities and research institutions. In general, these institutions develop construction robots to research robotic technology. Robots are not developed for the performance of specific tasks or projects, but to develop new robotic technology. In addition, these institutions lack the skills and motivation for marketing their robotic developments. As such, construction companies must become more active in the research and development of construction robots. Participation in the research and development of construction robots would reap two benefits:

a. The United States gaining its share of the construction robot manufacturing business.

b. General acceptance and a change in attitude towards the capabilities and use of robots in construction.

#### 7.2.4 Open Lines of Communication

As the use of construction robots increases, management officials must maintain open and honest communication with its workers and the local population. Only through open and honest dialogue will the use of construction robots be accepted. If the firm intends to purchase a robot, tell the workers before the robot arrives at the loading dock. If the purchase of the robot will result in job transfers or displacement, managers should inform the pertinent workers (not only the workers being replaced or transferred, but also their work mates) in advance. Failure to communicate openly will result in job dissatisfaction, protests, and a general reduction in productivity.

#### 7.2.5 Government Incentives

To stimulate the use of construction robots, the federal and state governments should offer incentives for purchasing <u>and using</u> construction robots. Incentives may take the form of tax credits, subsidized loans, or other programs. Any incentive should be tied to the actual use of the construction robot after purchase, preventing the contractor from letting the robot sit idle.

### 7.3 SUMMARY

In summary, the United States construction industry must start focusing its future operations on the use of construction robots. Robots are proven and profitable. Conservative attitudes must be swept aside and the construction process reorganized to include robots. In terms of the development and use of construction robots, the gap between the United States and other countries (particularly Japan) is presently small and can be closed quickly. If the U. S. construction industry continues to delay the implementation of robots in the construction process, it may face dire consequences in the near future:

productivity will continue to decline, costs will rise, and decreasing business and income. Construction contracts will be awarded to firms which are more productive and cost effective; without a doubt, these firms will be using robots.

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