8-1-1987

A Survey of Robotics Technology in Construction

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ATLSS Report No. 87-04

LEHIGH UNIVERSITY

August 1987

ATLSS

An NSF Sponsored Engineering Research Center

PREFACE

The ATLSS Center

The ATLSS (Advanced Technologies for Large Structural Systems) Center is one of a limited number of Engineering Research Centers currently sponsored by the National Science Foundation (NSF). The goal of the Engineering Research Center Program is to foster cooperation between universities and industries in the United States in various areas of technology that are important to the national economy. The objective of this cooperation is to enhance the competitive position of these industries relative to the rest of the world.

The ATLSS Center is focused on the construction industry, a $300 billion industry in the United States. Through the support of NSF, the Commonwealth of Pennsylvania, and its industrial partners, ATLSS performs fundamental and applied research that will benefit and strengthen the construction industry in the U.S. The research performed by ATLSS is organized into three thrust areas:

1. **Advances in Design Concepts** - research and development devoted to design problems in construction

2. **Innovations in Fabrication and Construction** - related to development and application of new technologies (e.g., robotics, automation) to the operational aspects of construction

3. **In-Service Monitoring and Protection** - R&D related to the preservation and maintenance of large structures after they are erected.

The ATLSS Construction Robotics Project

The survey documented in this report is part of a larger ATLSS project aimed at developing construction robotics technology in the United States. The project falls within the scope of the second ATLSS thrust area: innovations in fabrication and construction. The objective of the project is to study the opportunities for the application of robotics technology in the construction industry, and to design, build, and test one or more prototype robot systems for specific tasks in construction. The goal is to establish a leading research position for the ATLSS Center in the development of construction robotics.

The Lehigh faculty and student participants in the project, with departmental affiliation given in parentheses, are: Mikell P. Groover (Industrial Engineering), N. Duke Perreira (Mechanical Engineering), Cemal Doydum (IE Graduate Student), Richard Smith (ME Graduate Student), Nicholas G. Odrey (Industrial Engineering), Lynn S. Beedle (Civil Engineering), and V. Tuncer Akiner (Art and Architecture). Also included is B. Vincent Viscomi, Professor of Civil Engineering at Lafayette College.

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ABSTRACT

This report documents a survey of the significant research and development efforts in the field of construction robotics. The technology of robotics has developed largely to meet the needs of the manufacturing industries, where an industrial robot can be defined as a general purpose machine that is programmed to move its arm for loading production machines, spot welding, and similar applications. In these applications, the robot performs repetitive tasks at a single location. By contrast, construction robots would have to operate at more than one location, by possessing either mobility or a large work volume (e.g., a large crane). This requirement relates to the fact that construction tasks, while often repetitive in terms of work cycle, must be accomplished at different locations at the work site. The robot would therefore be required to move or be moved around the site.

In addition to mobility, construction robots would need to be more intelligent than robots used in manufacturing. Robot intelligence refers to the machine's capacity for autonomous control over its own operations. A higher level of autonomous control would be required of construction robots than manufacturing robots because the tasks at a construction site are less organized in terms of methods and workplace design. This requires construction workers (or robots which are substituted for them) to interact with their work environment, deal with variations in their tasks, and make decisions more than their factory counterparts.

Construction activity can be divided into nine phases. These phases are: surveying, excavation and grading, preparing the foundation, formworks, framing, installing flooring and roofing, installing walls, finishing, and demolition. Demolition is needed to dismantle and remove the building, bridge, or other structure at the end of its life cycle.

The survey presented in this report examines the achievements that have been made in the development of robots and related machines to perform the various activities in these nine construction phases. Approximately 60 development projects, including some that have resulted in commercially available products, are reviewed in the report. Certain application areas, such as surveying and reconnaissance, handling materials at the construction site, tunneling, concrete pouring and finishing, and demolition operations, have seen significant progress. In addition, certain technological advancements, such as robots that are capable of walking, are occurring that will help to provide construction robots with the required capabilities to perform tasks at the construction site. The Japanese have been especially productive in developing new applications of robotics in construction.

INTRODUCTION

Purpose and Scope of the Report

The purpose of this report is to survey the important research and development that have occurred in construction robotics. Examples will be cited in which robotics technology has been directly applied to construction tasks. While the term construction robotics is used here, the scope of the report will go slightly beyond this specific applications area. It will also include:

- Related developments in the more general area of construction automation (which includes construction robotics)

- Examples of robotics technology applied to problems that are outside of construction, but which might be applied in construction.

In some cases, most notably in Japan, the research has developed sufficiently to permit the installation of robots in the field on a pilot basis. Examples of these instances will be cited.

The survey has focused on robotic machines that have been developed for operation at the construction site. We might refer to these machines as "on-site" robots. The report gives little consideration to "off-site" machines that are used in the factory or fabricating shop to prepare components that are subsequently shipped to the construction site. This second category of robot is represented by today's commercially available robotics technology, commonly called industrial robots. This technology is covered elsewhere (e.g., reference [12]), and is not within the scope of the current survey.

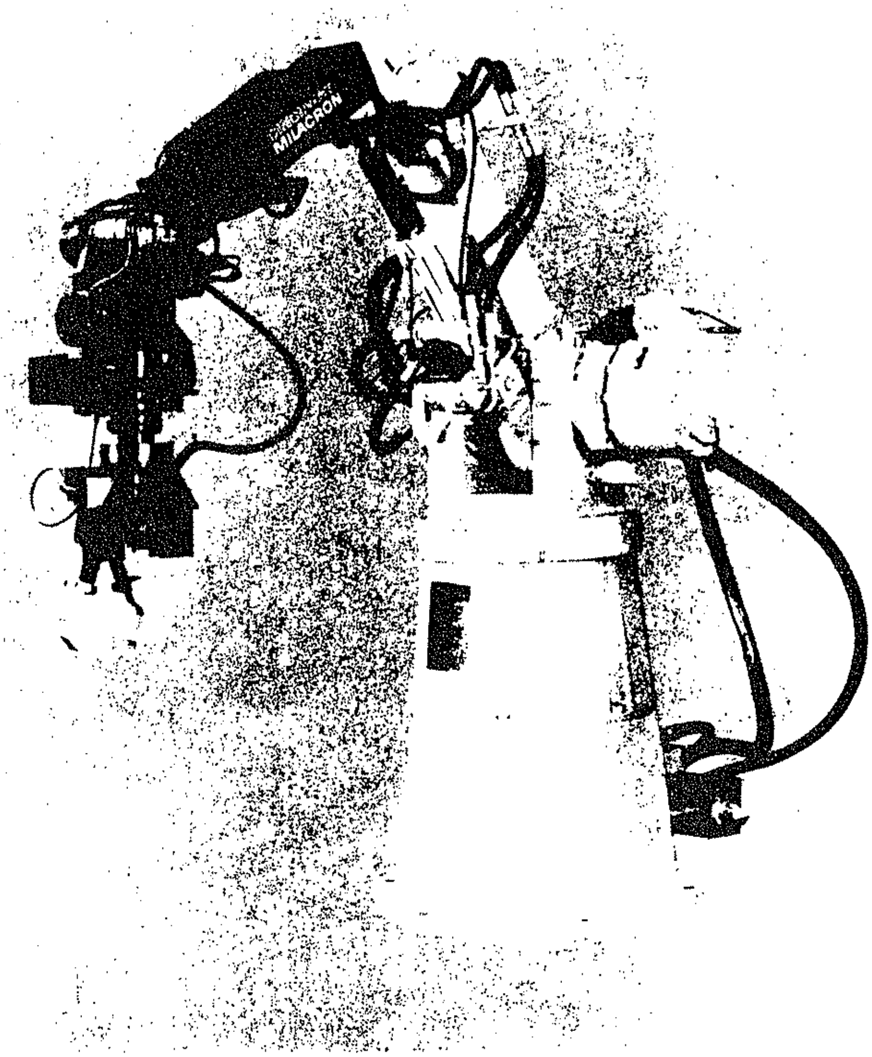
In addition, this report is not concerned with certain types of robotic machines that might be associated with the operating aspects of structures. For example, we do not examine developments in the area of security robots that might be used to roam through a building, using their sensors to detect intruders or other problems. These types of machines, although they certainly represent an important new technology area in the operation of a building, are not surveyed in this report.

Before presenting the results of the survey, it is appropriate to define several terms related to robotics - terms that will be used throughout the report.

What is a Robot and What can a Robot do?

An **industrial robot** is a general purpose programmable machine that possesses certain anthropomorphic, or human-like, characteristics. The most common human-like characteristic of a robot is its arm, or manipulator. The robot can be programmed to control its manipulator through a sequence of motions in order to perform some useful industrial task. An industrial robot is illustrated in Figure 1 below.

Figure 1 - A typical industrial robot used in manufacturing applications. The robot's manipulator consists of a series of joints and links that can be controlled in a coordinated fashion to perform useful tasks. This robot is hydraulically operated. (Courtesy of Cincinnati Milacron.)



Most robots today are used in manufacturing plants to perform a variety of industrial tasks. We have previously referred to these robots as off-site machines. The typical applications of today's industrial robots include: transferring parts from one location to another, loading and unloading production machines, spot welding automobile bodies, and spray painting. Most of these tasks are relatively simple, and although the applications themselves are diverse, they have certain characteristics in common. These characteristics are presented in Table 1.

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Table 1 - Characteristics of Robot Applications in Manufacturing

1. The work environments are hazardous to humans. Therefore an advantage is gained by removing the human worker from the environment and substituting a machine (the robot) in his/her place.

2. The tasks are repetitive. When a human worker performs the work, the tasks involve the repetition of the same simple work cycle over and over, with little or no skill or judgment required. Robots can be programmed to perform most tasks that fit this description.

3. The work is performed at a fixed location. It does not require the robot to move away from a given workplace.

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Not all industrial robot applications have all of these characteristics, but they often do. When robot experts perform a survey of a manufacturing plant to determine potential operations where robots might be used, they will typically include these three characteristics in their checklist of "what to look for."

The application characteristics envisioned for an "on-site" construction robot would be similar in some ways to those presented in Table 1. For instance, the work environment at the construction site often has dangers and hazards for the workers. Construction work for tall buildings and large bridges exemplify these dangers. In addition, many of the tasks performed by the robot in construction would be repetitive to a large degree.

However, there are additional capabilities that would be required for the construction robot which would not necessarily be needed by its manufacturing counterpart. One is the capability to operate at different locations at the construction site. To achieve this capability, the construction robot would have to possess either: 1) a large work volume or 2) mobility.

The term **work volume** refers to the space within which the robot can manipulate its wrist to perform useful work. An example of a robotic construction machine possessing a large work volume might be a tower crane that performs some of its movements under automated control.

Mobility refers to the capacity to move about the work site to perform repetitive tasks. In many construction operations, the human worker must perform similar tasks at different locations around the site. To accomplish these tasks, the worker must move or be transported to the new locations. A robot performing these same functions must also have the capability to move (or conveniently be moved).

A second feature that seems to distinguish a construction robot from a manufacturing robot is the requirement for a higher level of judgment and feedback sensing. In essence, the construction robot must be more intelligent than most robots that perform manufacturing-related tasks. The reason why this greater intelligence is needed is to cope with the more significant variations in the work activity performed by construction workers. Each variation from the normal work cycle requires a compensating response, and the robot must be able to sense the variation and respond accordingly.

The features of construction work that correspond to the manufacturing application characteristics of Table 1 are summarized in Table 2.

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Table 2 - Likely Features of Robot Applications in Construction

1. The work environment is often dangerous and hazardous for human construction workers.
2. The tasks are repetitive. Many tasks performed by the human construction worker are repeated over and over.
3. The work requires mobility. Construction work is performed at various locations around the work site.
4. The work requires intelligent-like behavior. Sensory perception, decision-making and judgment, are required to deal with variations in the work.

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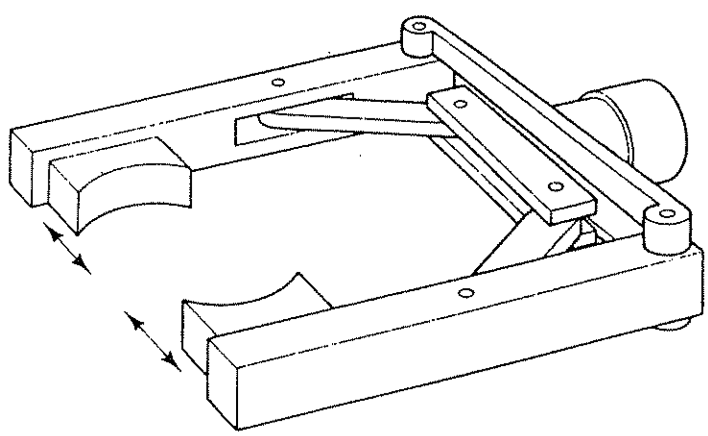
Other Terms Used in Robotics

Three other terms that are relevant in this report are teleoperator, telepresence, and end effector. A **teleoperator** is a machine that sometimes has the appearance of a robot. However, there are important differences between a robot and a teleoperated machine. A teleoperator is a manipulator or other mechanical device that can be operated from a remote location by a human worker. Such devices are used in hazardous environments, such as facilities with dangerous radiation and/or chemical hazards that preclude humans from being present to perform the work. The significant feature that distinguishes a teleoperator from a robot is that the teleoperator is controlled by a human operator rather than by a program. Therefore, the teleoperator has no capacity to act on its own. By contrast, an industrial robot accomplishes a defined work cycle under its own control.

Telepresence is defined as the acquisition of information by a human using sensors that are located remotely from the human. Telepresence is often combined with teleoperation in order to permit a human to operate equipment from a remote location.

An **end effector** is a device that is attached to the wrist of the robot that enables it to perform a specific task. It is often called the robot's "hand." The end effector permits the general purpose robot to be used for a variety of applications. There are two common types of robot end effector. The first is a gripper. Grippers are usually mechanical devices used by the robot to grasp parts or materials and move them from one place to another. An example of a mechanical gripper is illustrated in Figure 2. The second type of end effector is a tool. This permits the robot to perform various processing applications, such as spot welding, continuous arc welding, spray painting, and others. In each case a specialized tool is required to enable the robot to perform the particular application.

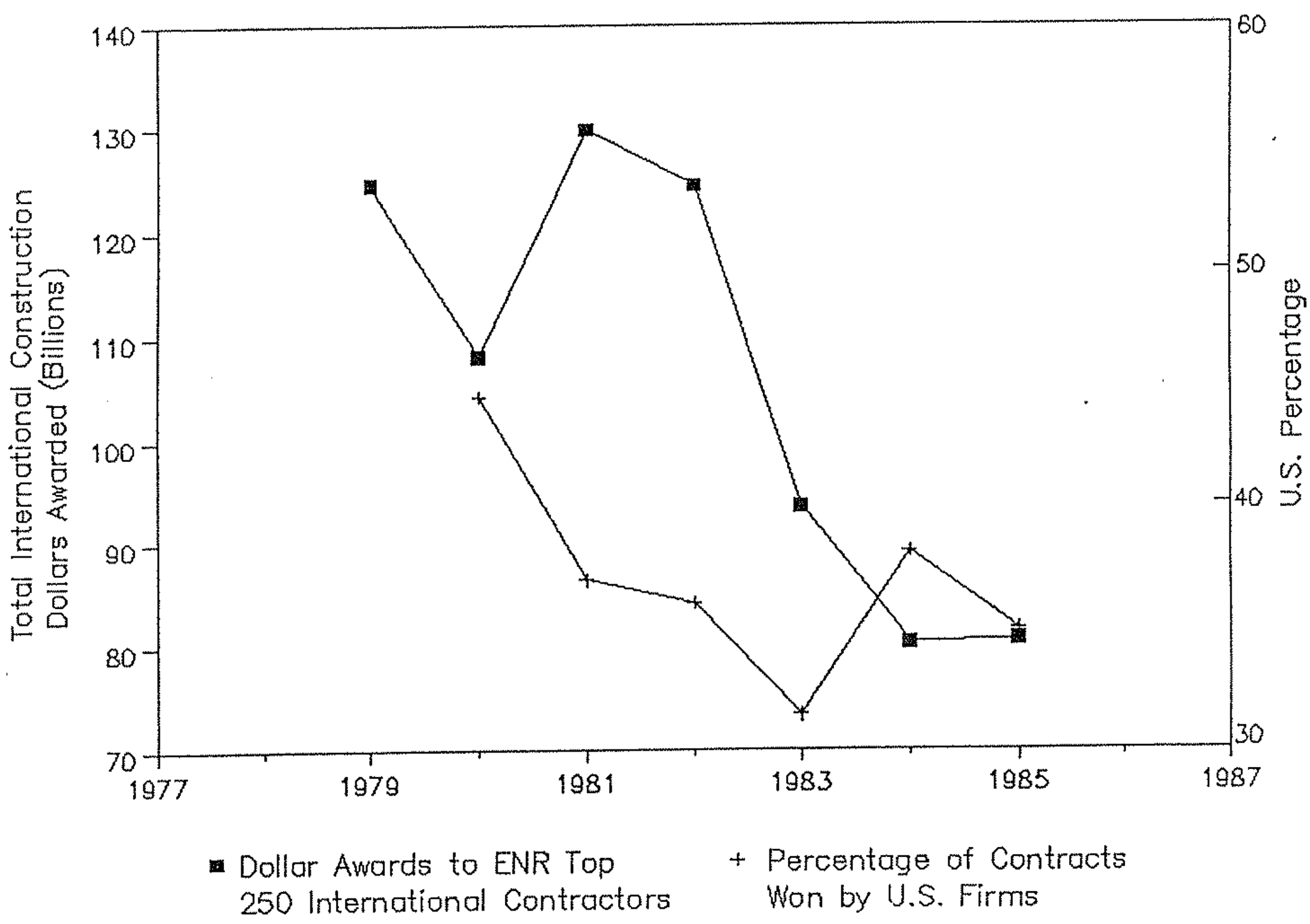
Figure 2 - Illustration of a mechanical gripper used in robotics to grasp objects such as parts. The gripper is a basic type of end effector used in robotics. (Reprinted from [12].)



JUSTIFICATION FOR ROBOTICS IN CONSTRUCTION

Construction in the United States comprises approximately 8% of the Gross National Product. It constitutes a $300 billion industry. Although the U.S. construction industry is a significant factor in our economy, international competitiveness and productivity in this industry have been declining during recent years. As illustrated in Figure 3, the U.S. share of the international construction market has shown a significant decrease since 1981. The plot indicates that the total amount of construction activity throughout the world has generally declined during the first half of the 1980s decade. In addition, the American share of this shrinking market is also decreasing. This is interpreted to indicate a loss of competitiveness by U.S. construction firms in the international marketplace.

Figure 3 - International construction contracts and the proportion of total work contracted to U.S. construction firms - 1979 through 1985. This summary was prepared based on Engineering News Record (ENR) data.



The use of robots in construction is likely to have an important impact on the construction industry. Assuming that the cost of a given robotic device were reasonable, continued escalation of the hourly wage for humans could be partially offset by the substitution of robots for human workers. Twenty-four hour per day operation using robots might become feasible in certain applications. Productivity would dramatically improve in the construction trades. Productivity is not the only reason for robots in construction. Using robots would provide the opportunity to remove human workers from potentially dangerous working conditions, thus improving safety in construction. In addition, robots can usually perform work tasks with more consistency than human workers, leading to higher quality.

Productivity, safety, and quality are three principal justifications for developing robotics technology for the construction trades. The following subsections will discuss these issues.

Productivity

Construction productivity, defined as Gross Product originating per man-hour in the construction industry, has shown an average annual net decrease of nearly 1.7% since 1969 [7]. The average of all industries for the same time period has been a net annual increase of 0.9%, while the manufacturing sector has posted an increase of 1.7% [37]. Annual productivity data reflect market conditions and fluctuate significantly. However, the average statistics show a definite negative trend in labor productivity for the construction industry.

Economists have used statistical analysis to determine the relative importance of the three principal factors which contribute to productivity growth: labor, capital investment, and technological innovation. The relative contributions of these factors [11] are:

Labor -	14%
Capital Investment -	27%
Technological Innovation -	57%

To illustrate the importance of technological innovation, consider the air transportation industry. Productivity in this industry is most appropriately defined as the product of people or goods moved multipled by miles travelled, divided by man-hours of labor input. Air transportation productivity in the United States has increased annually by 6.3% since 1947. The reasons for this productivity increase are fairly obvious: jet aircraft technology has allowed larger, faster planes to be built and computer technology has provided more efficient scheduling of flights. Thus, the technology has been the driving force behind the increases in productivity in air transportation.

In certain foreign countries, especially Japan, the use of automated and robotic equipment has increased the productivity of construction workers by improving the quality of work done, reducing the time required to perform certain tasks, reducing the number of workers required for a task, and removing the worker from the most hazardous jobs [49]. It should be noted that most of the Japanese projects are being developed by the construction firms themselves. In contrast, the majority of development work in construction robotics in the United States is not being done by the construction firms. The development effort is being accomplished by university research labs and small entrepreneurial companies.

Safety

Construction work is dangerous. The U.S. construction industry employs nearly 6% of the American workforce. Yet, the number of occupational injury and illness cases reported by construction workers comprises over 10% of all cases reported [38]. Except for mining, construction work was the most hazardous work during the period 1980-1984, according to a recently released report by the National Institute for Occupational Safety and Health [20]. The annual fatality rate among construction workers was 23.1 deaths per 100,000 workers, or an average of 952 deaths per year during the five year period of the study. This rate compares to the average of all workers of 9 deaths per 100,000 workers. (Miners had the highest fatality rate, equal to 30.1 per 100,000 workers, or an average of 315 deaths per year.)

There are other indications of the dangers in construction, compiled from [38]; for example, the number of workers reporting work-related injuries and illnesses. Over the last decade, an average of between 14% and 15% of American construction workers have reported work-related injuries or illnesses annually, compared to between 7% and 8% for all workers. The severity of non-fatal injuries to construction workers may be judged by the fact that they miss approximately 120 workdays per 100 workers reporting injuries, versus only 60 days per 100 workers reporting injuries for all industries.

Quality

Quality represents a third reason for using robotics in construction. Many of the applications of industrial robots in manufacturing are justified, at least in part, on the basis of product quality. For example, robots used for spot welding in automobile body lines are capable of positioning the welding gun with much more consistency than human workers. This results in a more consistently made product. Similar results are obtained in robotic spray painting and arc welding. There is every reason to believe that construction robots would be capable of performing certain repetitive tasks with greater consistency than human construction workers, leading to a higher quality structure.

In addition, robots can be used to perform inspection operations, without the fatigue factor and accompanying errors that are common when humans perform these tasks. Examples will be presented in this report of robotic systems being used to accomplish inspection tasks in the construction trades. Detection of poor adhesion of wall tiles to the wall surface is one instance of these applications. These types of systems improve quality in construction.

CLASSIFICATION OF CONSTRUCTION TASKS FOR ROBOTICS

There are various ways in which to organize and classify construction work. Our purpose here is to classify it in a way that lends itself to analysis for the application of robots in construction. Specifically, this study considers the types of features required of a robot to perform various construction tasks. These features include the robot's configuration and its advanced capabilities such as mobility and autonomous control.

In this section, two ways to classify construction work are presented. The first method is one developed by Warzawski [41], [42]. The second classification is one suggested by the construction industry itself, and it is the classification that will be developed in more detail in this report.

Warszawski Analysis

Most construction work consists of various job tasks that occur over and over. The most common job tasks found in construction are shown in Table 3, an adaptation based on [41]. These job tasks constitute the basic work elements of construction activity.

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Table 3 - Basic Building Tasks and Activities identified by Warzsawski.

Attaching - Positioning & attaching a small object to a larger one. Examples include attaching hangers, inserts, partition boards, siding, shingling.

Building - Placing blocks with a desired pattern. Examples include cinder blocks, bricks, or stone masonry.

Coating - Discharging a liquid or semi-liquid substance on a surface. Examples include painting, plastering, spreading mortar or glue, caulking.

Connecting - Connecting of a component to an existing structure. Examples include bolting, nailing, riveting, welding; disconnecting.

Covering - Unrolling sheets of material over a given surface. Examples include vinyl or carpet flooring, roof insulation, wall fabric.

Demolishing - Breaking a structure or structural element into smaller pieces. Examples include tearing, sawing, smashing, breaking.

Excavating/Grading - Moving large quantities of earth. Examples include foundation digging, grading for roads.

Table 3 - continued.

Finishing - Applying continuous mechanical treatment to a surface. Examples include grinding, brushing, smoothing, troweling.

Inlaying - Placing flat pieces on a surface in a pattern. Examples include tiling, wood planks, flooring.

Inspecting - Non-intrusively examining a structural element. Examples include weld inspecting, level sensing, corrosion detection.

Jointing - Sealing joints between vertical elements. Examples include joints between precast concrete elements or between partition boards.

Materials Handling - Delivering materials from one location to another according to a schedule. Examples include supplying bricks, blocks, shingles, mortar.

Positioning - Placing a large object at a given location in a given orientation. Examples include erection of steel beams, precast elements, formwork, scaffolding.

Surfacing - Pouring, forming, or casting of a material onto a surface or frame. Examples include pouring concrete, asphalt, tar; shotcreting.

Surveying - Developing a functional map of the surroundings. Examples include surveying, mapping.

Testing/Sampling - Intrusive testing of a structural element or its environment. Examples include weld sampling, air testing, seabed sampling, soil sampling.

Tunneling - Creating a passageway underground for mining, transportation tunnels, utility tunnels, etc.

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By analyzing these basic job tasks in terms of such requirements as strength and size, anatomical features, mobility, and control, Warszawski identified four potential robot types to perform construction tasks. These types are:

1. **Assembly robot.** This robot manipulator would assist human construction workers by lifting and positioning large components (e.g., steel beams, precast concrete members) during erection of a building. It would be a large robot, with lift capacity of several tons, and the capability to move about the work site to perform its functions at different locations.

2. **Floor finishing robot.** This robot would be used for horizontal finishing tasks, such as troweling, glue spreading,

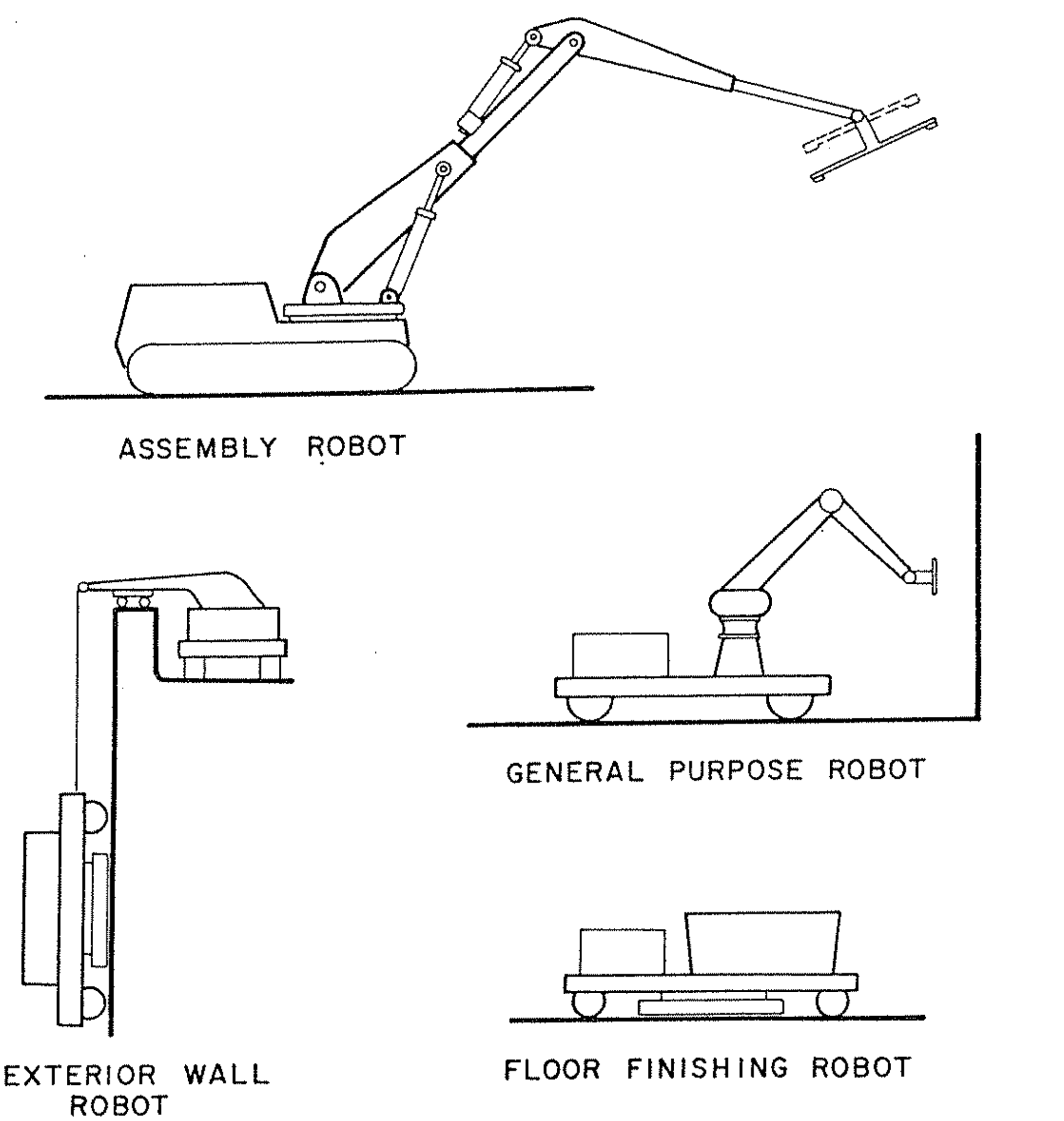
brushing or sweeping operations.

3. **Exterior wall finishing robot.** This robotic system would be used for exterior finishing operations on vertical walls. The operations might include: painting, plastering, weatherjointing, and inspection. One argument for such systems is the safety issue: it would eliminate the need for human workers to perform these tasks at the high elevations on with exterior walls.

4. **General purpose robot.** This would be a versatile machine for performing interior tasks such as painting, grouting, or nailing.

The general configurations of the four types are illustrated in Figure 4. These four robot types do not perform all of the tasks and activities listed in Table 3. Some of the tasks (e.g., surveying, excavating, testing and sampling) would have to be accomplished by specialized robotic machines.

Figure 4 - Four types of robot configurations suggested by Warszawski [41], [42]. (Reprinted from Ref [41].)



Construction Industry Classification

The construction industry typically defines its activities by phases in the life cycle of a structure. Table 4 presents the nine phases of construction. The terminology used in Table 4, although usually applied to buildings, is generally applicable to bridges, dams, highways, and most other construction projects. For different types of construction, the relative importance of these phases will vary.

Table 4 - Standard Construction Phases, listed in order of occurrence during the life cycle of the structure.

Activity performed	Symbol in this report	Brief description
Surveying	SUR	Develop a map of an area.
Excavation-Grading	EXC	Movement of earth to prepare site.
Foundation	FOU	Preparation of ground to provide solid base for structure.
Formworks	FOR	Preparation of forms to establish the shape of the concrete structure.
Framing	FRA	Erection of steel or concrete structural skeleton.
Floor Systems	FLO	Installing the subfloor and flooring for each level of a structure.
Wall Systems	WAL	Installation of walls using prefabricated panels, masonry work, or other methods.
Finishing	FIN	Electrical and mechanical work, painting, tiling, etc., to make the structure functional and attractive for users.
Demolition	DEM	Dismantling the structure at the end of its useful life.

Each of the nine phases in Table 4 involves a series of activities that is carried out generally by independent subcontractors. These activites are distinguished from each other in that they involve different types of construction materials, equipment and tools, and worker skills.

The term "construction material" includes all kinds of physical entities that are added to the building during the construction process. The different materials have different physical characteristics. They may be fluid, such as wet concrete, or solid, such as steel rods; they may be small such as bolts and nuts, or large such as steel columns. The type of material is important in robotics because the robot must be designed to handle the particular material.

A construction activity can also be characterized by the types of equipment and tools that are used. An activity may involve tools as small and simple as drift pins and wedges or equipment as large and sophisticated as a tower crane. The equipment and tooling used in construction are important because, if a robot is to be involved in the work, it must be equipped with the proper tool to perform its task. In manufacturing, the task that a robot is capable of performing is usually determined by the type of end effector attached to its wrist. The same robot can be used for various applications simply by changing the robot's end effector. It is possible that future commercial robots for construction will permit the same flexibility of application through the use of interchangeable end effectors.

The skills of the workers needed to accomplish a task have considerable importance in terms of analysis for robotics. Worker skill can be considered to be the level of autonomous control exercised by the worker over his task. Autonomous control refers to the capacity to perform complex work functions and to deal with variations in the job by making appropriate decisions. This is a characteristic that we have previously called "intelligence" in Table 2. The worker skill level required in a given construction task can sometimes be reduced to the accuracy and repeatability required to perform the task. Accuracy and repeatability are specifications often used in industrial robotics, indicating the capabilities of the robot to position and orient an object or tool in the workplace.

The Nine Construction Phases and How Robots are Used

In this subsection of the report, the construction phases outlined in Table 4 are discussed in more depth. In addition, the research and development efforts in robotics directed at these phases are also discussed. In some of the phases, relatively little has been accomplished to automate the activities associated with the phase.

Each robot development activity discussed in this subsection is described in more detail in the Appendix. In addition, other projects not mentioned in this subsection are also documented. A total of 61 research and development projects are included (35 in Japan, 24 in the United States, and 2 in Western Europe). The purpose of the Appendix is to provide a comprehensive compilation of the R&D activities in construction that have occurred during the past five years or so. Alphanumeric symbols surrounded by parentheses - e.g., (SUR1), (EXC3), (DEM9) - used in the current subsection refer to the listings in the appendix.

1. SURVEYING. The purpose in surveying is to develop a map of a given area. Surveying is done to define the terrain of the construction site or to develop a topographical layout of a large area. This work is usually accomplished by certified surveyors using transits and other means to precisely measure and document the terrain.

An activity related to surveying is inspection performed in dangerous areas such as sea bottoms or nuclear sites. The work is done by relatively sophisticated machines and a large amount of topographical (or chemical) data is required to form the data base.

A good deal of development effort has been directed at the problem of automating many of the tasks in surveying. Much of the interest in automating this activity stems from the military, which perceives the need for highly instrumented and autonomous vehicles roaming in enemy territory to gather intelligence data. Some development effort has been devoted to the more traditional surveying tasks. Also, because of dangers to humans in hazardous environments, teleoperator devices have been devised to collect data and transmit it back to a safe location.

The robotic vehicles that have been developed for use in this application area are mobile. Some of the vehicles are teleoperated; that is, their paths and actions are determined by a human operator located remotely from the vehicle. Sensors are incorporated into these systems to take measurements and data about their environments. The human operator uses the environmental information to guide the vehicle. This is an illustration of telepresence.

In addition to teleoperated machines, there are autonomous robots which do not need human assistance to do surveying type tasks. This means that, given the target location, these robots are able to plan their own paths and motions and make necessary adjustments in them based on sensory data.

The Appendix includes 12 projects involving the surveying robots. Some representative examples include:

- Kokusai Denshin Denwa's Seabed Monitoring Robot (SUR2).

- Remote Reconnaissance Vehicle (SUR3), a teleoperated vehicle designed for observing damage in the containment building at

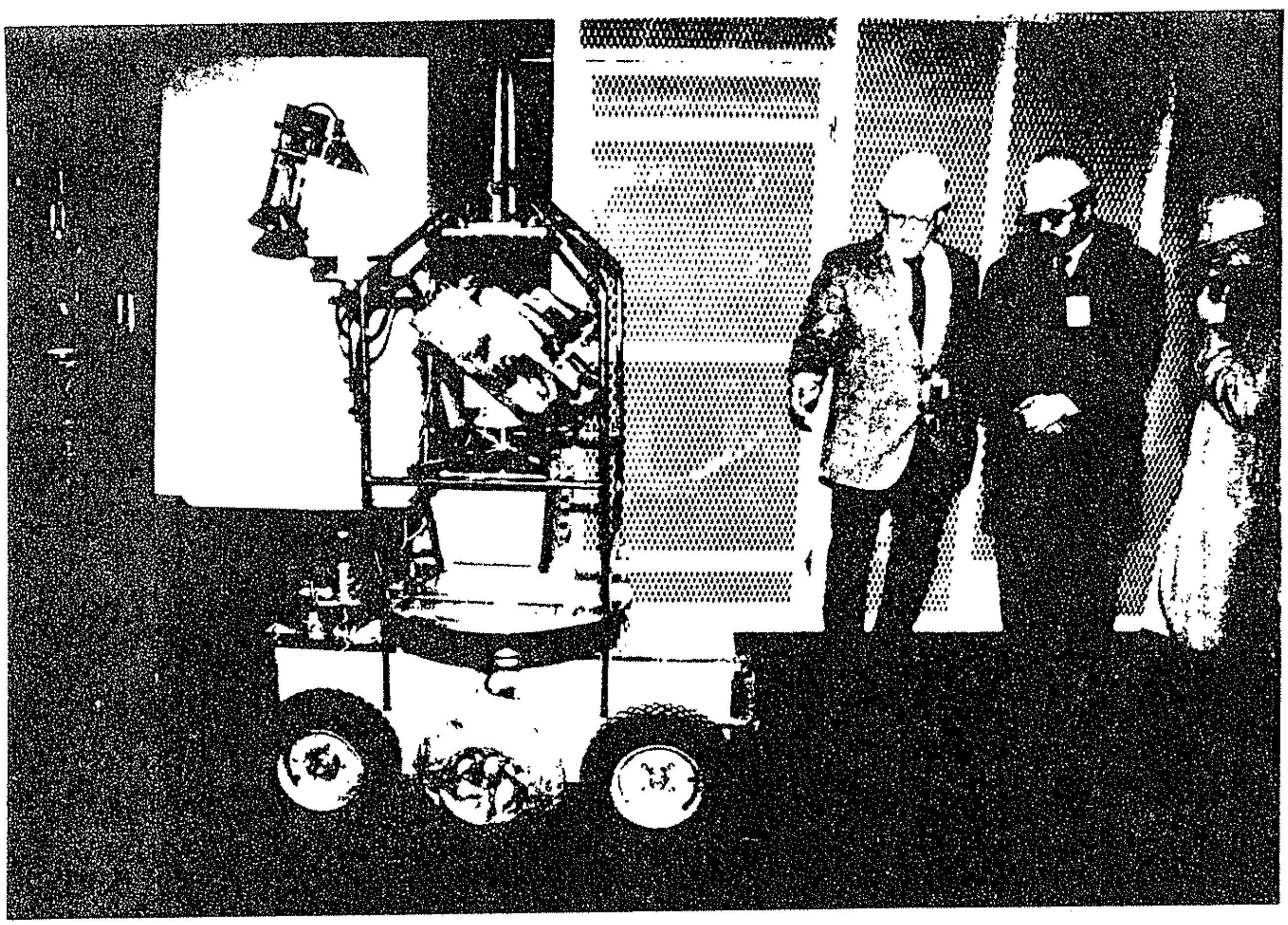
Three Mile Island Unit 2, which was made inaccessible to humans by the nuclear accident in 1979. This vehicle, shown in Figure 5, was developed by the Construction Robotics Laboratory at Carnegie Mellon University.

- Komatsu Ltd.'s Remotely Controlled Underwater Surveyor (SUR6), called ReCUS, a robot for underwater surveying.

- Terragator (SUR7), also developed by the Construction Robotics Laboratory at CMU.

The "Seabed Monitoring Robot" and ReCUS illustrate that some of the surveying robots are designed for underwater use, an application area considered important by the Japanese. A U.S. Navy teleoperated vehicle for underwater use is illustrated in the Appendix (SUR12).

Figure 5 - Remote Reconnaissance Vehicle developed by the Robotics Institute at Carnegie Mellon University. This vehicle is operated in the damaged Unit 2 of the Three Mile Island nuclear power plant for remote observation (SUR3). (Photo was taken during a visit to TMI-2. Personnel shown (left-to-right) are Bechtel Engineer at TMI with Professors Odrey and Groover.)



2. EXCAVATION-GRADING. Excavation and grading operations involve the movement of earth from one place to another. The movement of earth may be entirely within the construction site, or it may involve bringing materials into the construction site or the removal of materials from the construction site to an off-site location. Grading, foundation digging, tunneling, and trenching fall into this category.

Excavation is done by large, mobile equipment such as bulldozers and power shovels. The operators must possess the necessary training and skills to operate the equipment and comply with safety regulations. A high degree of hand-eye coordination and manual dexterity is generally required. When operated in this manner, excavation and grading equipment is highly mechanised, with little or no automation used in the operation. The precision required in excavation and grading is usually generous, sometimes measured in feet for rough grading operations.

As in the case of surveying robots, there have been efforts to automate certain excavating operations, or to provide for remote operation of the equipment (teleoperation), in order to remove the workers from the operation site. Research in this area can be divided into two categories:

1. Enhancement of conventional excavation equipment by means of microprocessors and sensors. These enhancements are designed to make the equipment easier for the operator to use.

2. Original design of special robotic systems. These efforts involve an analysis of the basic functions to be accomplished and the design of a new machine to perform the functions with little or no human involvement.

Eight examples of these efforts to automate tasks associated with excavating and grading are reported in the Appendix. The projects include:

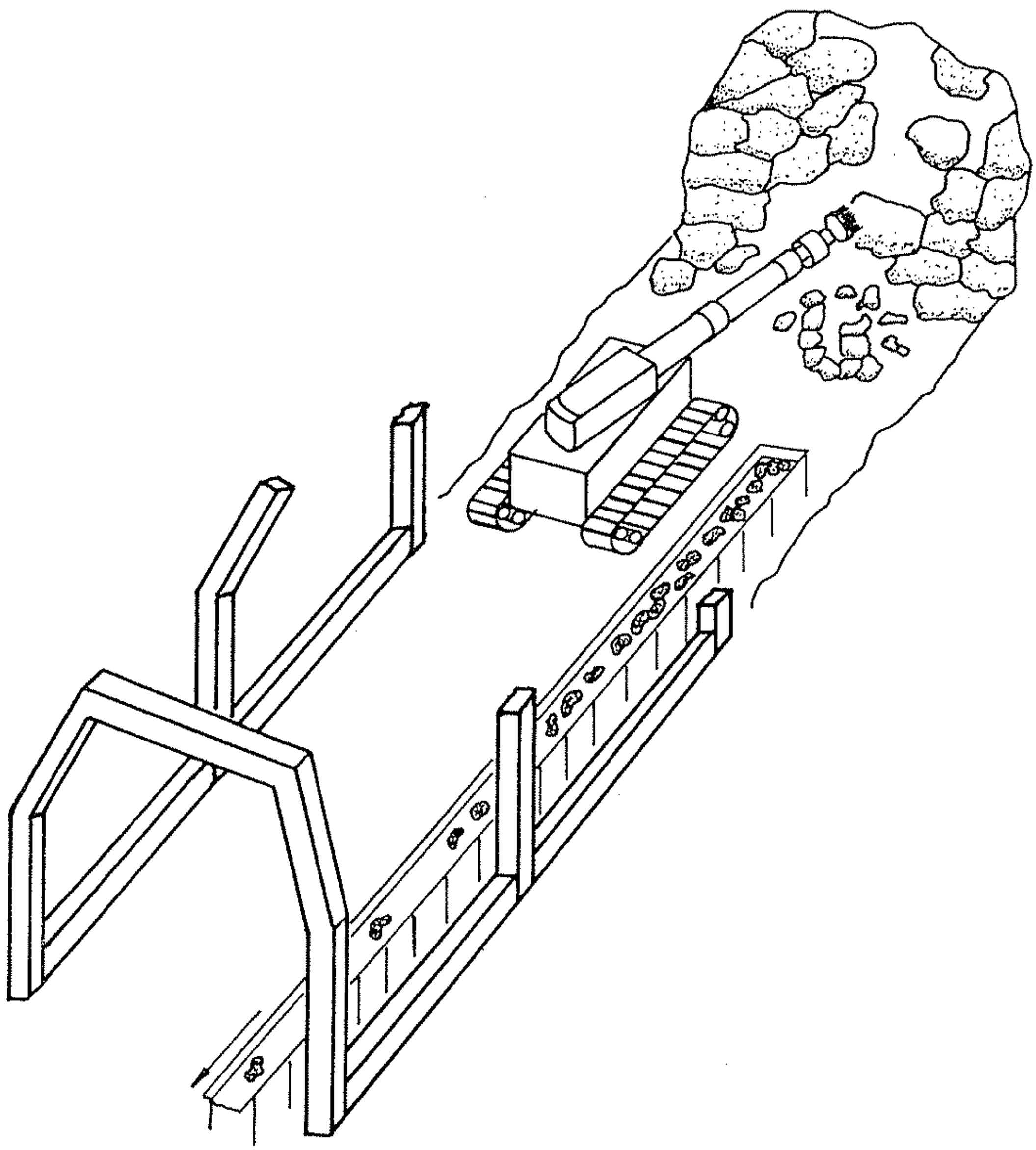
- The Generex (Second Generation Robotic Excavator) project at Carnegie Mellon University (EXC2), which seeks to create an autonomous robotic device for unearthing buried utility piping.

- Shield Driving Automatic Control System (SDACS) a system developed by Hazama-Gumi in Japan to automate tunneling operations for subway lines (EXC6).

- Laserplane Grade Control System (EXC8), a product developed by a company called Spectra-Physics. This is a sensor and controller to automatically set the height of a bulldozer blade during grading operations.

There is much interest in the coal mining industry in developing robotic machines that would perform tunneling and related operations associated with mining. As indicated in our Justification for Robotics in Construction, mining is the most hazardous of all industrial jobs. Figure 6 illustrates one possible form of a coal mining "robot."

Figure 6 - Artist's drawing of robotic coal mining for tunneling and scooping coal from a mine face. (Redrawn from [12].)



3. FOUNDATION. Foundation operations are concerned with the preparation of the ground on which the construction will be done. The purpose of this preparation is to provide a solid base onto which the structure can be built without subsequent settlement or movement. Depending on the type of structure and the nature of the soil, foundation operations can constitute a major portion of the construction schedule.

To accomplish the foundation preparation, the ground may be reinforced by steel or concrete elements called piles. These piles are inserted deep into the earth by pounding them with a heavy powered hammer to drive them downward. Problems encountered during this work include: difficult-to-penetrate soil, rocks in the soil, dulling of the piles, and deflection of the piles from the intended insertion line. The powered hammers used to drive piles into the ground operate more or less in an untended mode, once they have been set up at a given location.

The incorporation of computerized monitoring systems to identify and deal with the problems enumerated above would make the pile driving work more effective. To our knowledge, little or no work has been done to utilize robotics in this phase of construction. We are not able to report any examples of robots designed to perform foundation-preparation operations.

4. FORMWORKS. Concrete structures require the use of wooden or steel forms into which the fresh concrete is poured and compacted. In the case of the wooden forms, the fabrication of these forms constitutes a special branch of carpentry. Wooden or steel, all forms must be assembled in place where they will be used. In general, formworks involve such tasks as positioning (erection of the forms), connecting (nailing, bolting) and disconnecting the forms. Scaffolding, used for working at difficult-to-reach, usually elevated locations, uses techniques and equipment similar to those used in formworks.

Our survey disclosed no examples of robotic machines that are used exclusively for Formworks activities. However, a number of projects in the Framing category (following subsection) could also have potential uses in Formworks.

5. FRAMING. The frame or structural skeleton of a building may be constructed of reinforced concrete or structural steel. In a reinforced concrete building, the structural components can be cast in place or precast in a remote production plant and then transported to the construction site. The assembly of these precast members is similar to the assembly of structural steel members, the procedure for which is described below. The positioning and connection of these framing members require handling and connection mechanisms, just as handling and connection are required in formworks. The connections in framing require more precision during assembly than those in formworks. In addition, there is generally no consideration given to disconnecting the framework since the structure is built to be permanent.

Consider the sequence of tasks in erecting a frame of a building using structural steel. In particular, let us consider the addition of a steel beam or girder to a steel column in a partially framed building. First, the beam or girder is hoisted and positioned in a general vicinity and orientation near the column within the existing structure. This is typically done by means of a manually operated overhead crane. Next, the final position of the girder is established at the connection points. This is accomplished by steel workers, using crowbars and/or hammers to align the beam and secure it with drift pins or bolts. The attachment procedure requires an accurate positioning that is not obtainable by the crane operator alone. In some cases, the misalignment is sufficiently poor that the girder must be physically modified in order to fit with its mating members. The girder is then attached to the existing structure, usually with a second crew of steel workers, using high strength bolts and/or welds. Subsequent girders in the frame go through the same process until the frame is complete. After all girders and beams have been assembled in place, it is likely that the quality of the welds and/or bolted connections will be inspected before the frame is painted and coated with fireproofing insulation.

When bolting is used to connect the members of the structure, one of the problems that arises is misalignment of the bolt holes between the structural elements to be connected. To remedy this misalignment problem, the workers either enlarge the holes of one of the beams to make the holes match, or, in extreme cases, new holes must be drilled on site. This is not an easy task to accomplish on steel beams when it is done several stories up. In addition to bolting, welding is also a widely used connection method in framing.

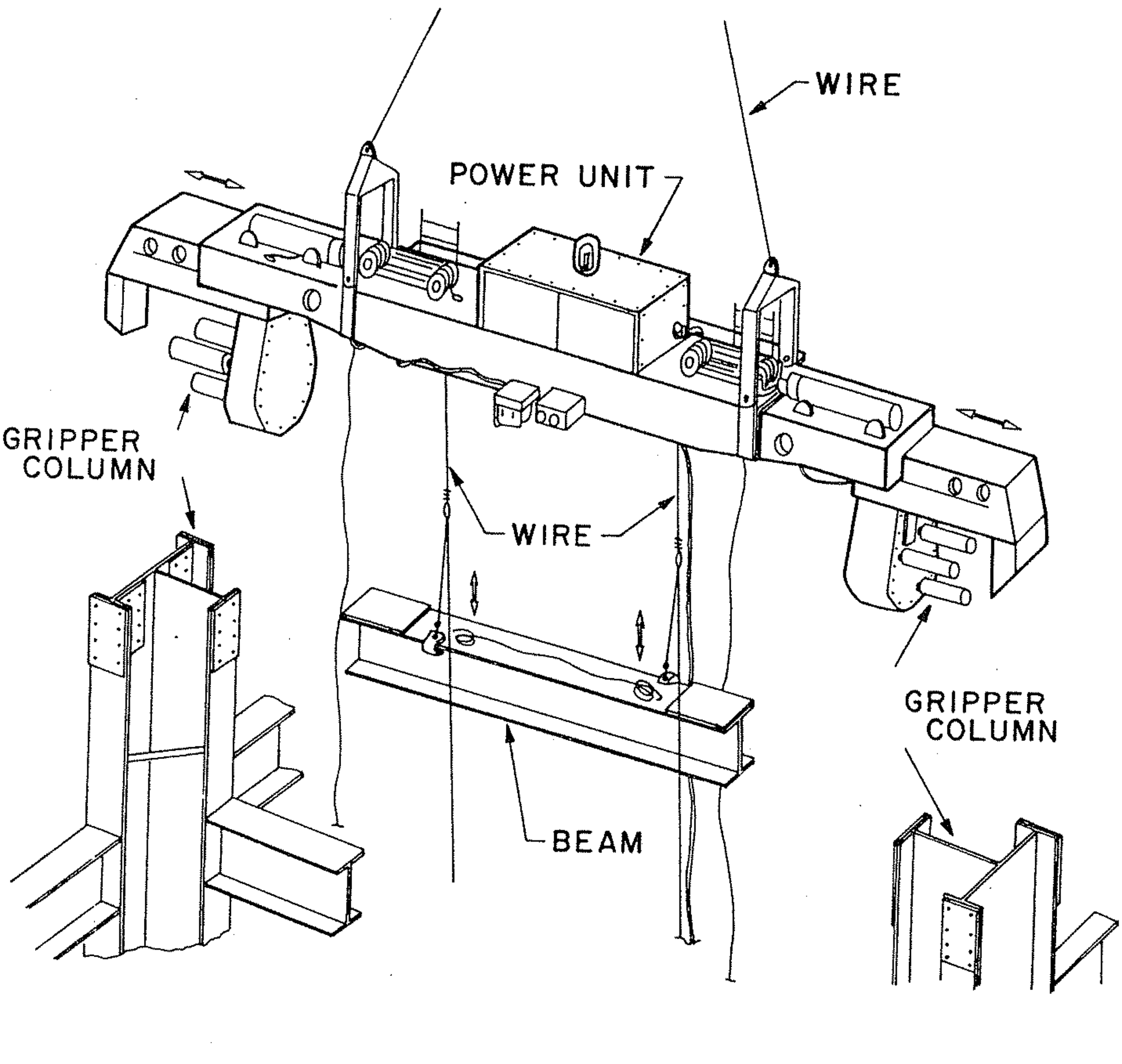
Since the erection of the structural members is done by moving large heavy components, cranes and other material handling equipment are often utilized, especially for large structures. The National Bureau of Standards has shown interest in this type of equipment, in a combined activity between its Robotics and Civil Engineering groups at NBS (FRA8). There are several examples of projects involving heavy rebar-arranging robots and overhead cranes, with the interest in this type of equipment being especially keen in Japan. Some examples of Framing automation projects include:

- Heavy Rebar Arranging Robot (FRA7), developed by Kajima Corporation in Japan to implement the handling tasks required in framing. It is capable of carrying 20 reinforcing bars and placing them at prearranged intervals. The labor cost reduction is significant.

- "Mighty Jack" (FRA9), a teleoperated device developed by Shimizu Construction Co. in Japan for positioning and aligning beams that are to be added to a partially framed structure. The device is illustrated in Figure 7.

- Robot Tower Crane (FRA10), a teleoperated crane developed by the Japanese firm Takenaka Komuten Co. This large crane is illustrated in the Appendix.

Figure 7 - Mighty Jack assembly machine (FRA9) for lifting and positioning steel beams during the framing phase of construction. The Mighty Jack is carried into position by a large tower crane and temporarily fastened to the existing structure for it to be operated. (Redrawn from [34].)



Mighty Jack (FRA9) and the Robot Tower Crane (FRA10) are limited in their operation to handling tasks. The connection of the frames would require the use of a dexterous robot manipulator or an intelligent tool that would facilitate the framework tasks performed by the workers. The enhancement of the current robotic handling systems by means of a connection-making mechanism would be a major step toward the automation of the frameworks phase of construction.

As suggested by the preceding paragraph, connections represent one of the major problem areas in heavy structures. The connections of a structure's frame are usually the locations where the structure is mostly likely to fail. This report addresses only the aspect of the connections problem related to making the connections during construction. Specifically, we are concerned with automating the task of connecting two (or more) structural members. There are two possible approaches that will be discussed here.

The first approach involves automating one of the current methods for making connections. The two methods used predominantly in modern construction are bolting and welding. In order to automate the bolting task, one prerequisite condition is greater accuracy and consistency of the components that are to be connected in order to avoid the misalignment problems discussed earlier. Misalignment of mating parts is also an issue in welding. When human welders perform the welding process, they can compensate for deviations and misalignments of parts. Industrial robots are sometimes used to perform continuous arc welding operations, and the control of welding robots is a major issue of research and development effort today. The quality of the welded connection can often be improved by employing robots, since a robot is capable of greater consistency in following a defined welding path than a human welder. However, this capability for consistent and repeatable motions is only useful when the component parts are extremely uniform, thus providing minimum deviations from the required welding path to be followed. In many practical applications, and construction welding is included in this group, the components possess irregular edges for which compensation is required during continuous welding. In these cases, the welding robot must be provided with some type of sensor device to track the welding seam and compensate for variations in mating parts.

The second approach involves the development of some new connections method, or a new adaptation of an existing procedure (e.g., welding or bolting). The new method would probably require changes in structural design, perhaps adopting a new technology or adapting a technology not presently used in construction. For example, some of the design-for-assembly principles developed for the design of mechanical and electronics products might by adopted in the design of large structural systems. Implementing the new connections technology might be facilitated by means of robotics. Predicting the nature of the new technology in this report would be speculative; however, this connections area is one of high interest to our ATLSS Center.

The authors of the present report believe that human workers will still be required to participate in the operations of making connections in construction for many years into the future. A robot or other automated device would be used to facilitate the task of the human worker, perhaps performing the task after being set up by the worker. The human would be present to monitor the process and to deal with problems and irregularities that might arise.

As in so many other tasks in construction, connection operations are performed at many different locations on the structure. If a robot were to perform the connection tasks, the issue of mobility arises. Under the preceding description of a connections robot working together with a human worker, it would not be necessary that the device possess mobility. However, it must be capable of being easily transported from one location to another by human workers in order to perform its function at different locations.

6. FLOOR SYSTEMS. Floor systems are basically composed of two parts: subfloors and floor finishing. Subfloors in reinforced concrete structures are an integral part of the building frame. This means that the subfloor and the floor elements are cast in place before proceeding to the next higher floor. In the case of steel structures, subfloors are added later as the construction progresses. Nevertheless, both floor systems require the pouring and spreading of the fresh concrete evenly on the floor space and then finishing it. Pouring, spreading, and finishing must be done one after another when the concrete is still wet. This is typically a dirty and labor-intensive job.

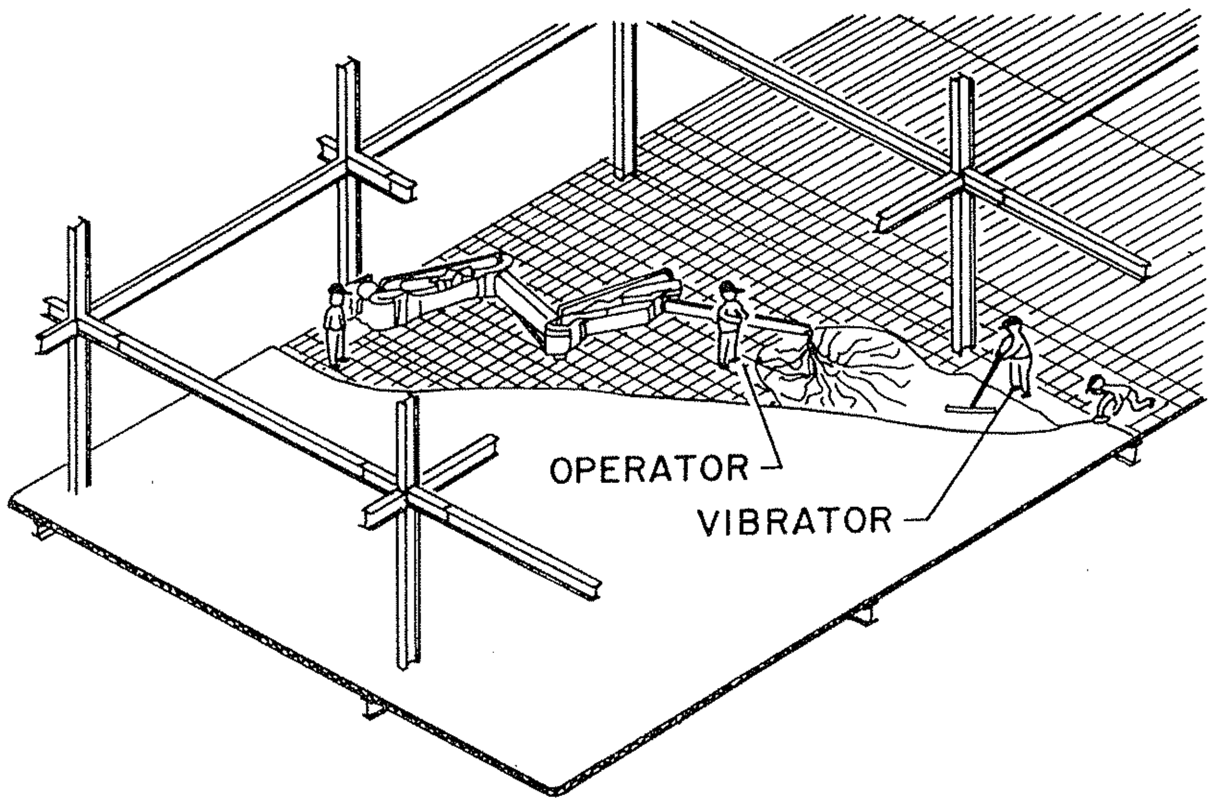
Special concrete distribution systems and concrete finishing robots are being developed and tested by Japanese construction companies. Two examples of these development activities are:

- Horizontal concrete distributor (FL01), developed by Takenaka Komuten Co. This system automatically distributes concrete onto the floor area. Figure 8 on the following page illustrates the operation of the Takenaka Komuten machine. The finishing of the slab is subsequently accomplished by automated finishing machines.

- Concrete Slab Finishing Robot (FL04), developed by Kajima Corp. in Japan. The machine, illustrated in Figure 9 on page 28, is designed to smooth the surface of a wet concrete floor after pouring.

These and other machines described in the Appendix indicate that the Japanese construction firms are developing highly mechanized and automated systems for accomplishing the installation of concrete floor systems.

Figure 8 - Concrete distributing robotic system (FLO1) developed by Takenaka Komuten. The general operation of the device is illustrated in the top drawing below. A diagram showing the details of the articulated arm is illustrated in the bottom diagram. The arm consists of a series of links, joints and pipes to position the nozzle and deliver the fluid cement to the floor. (Redrawn from [34].)



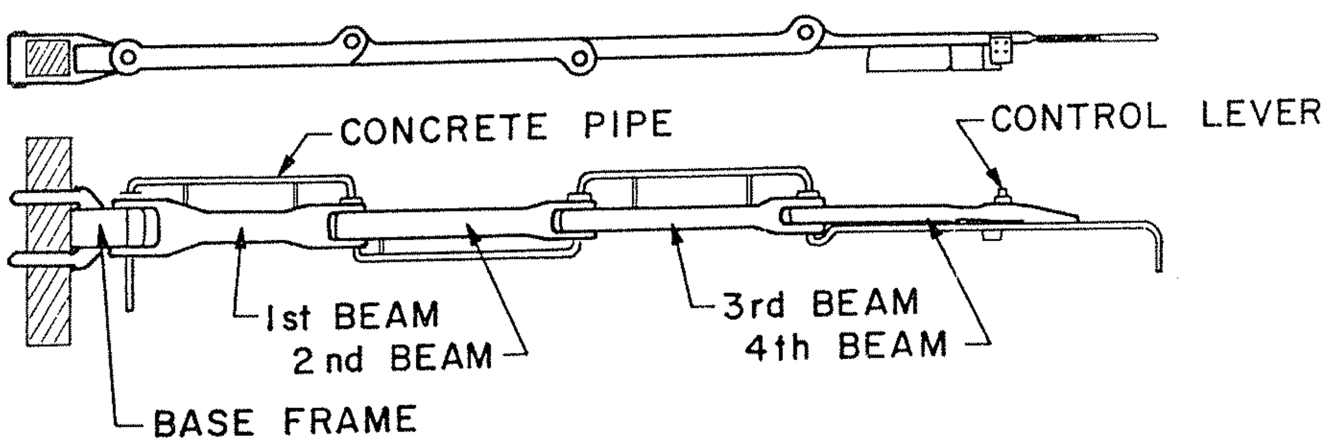
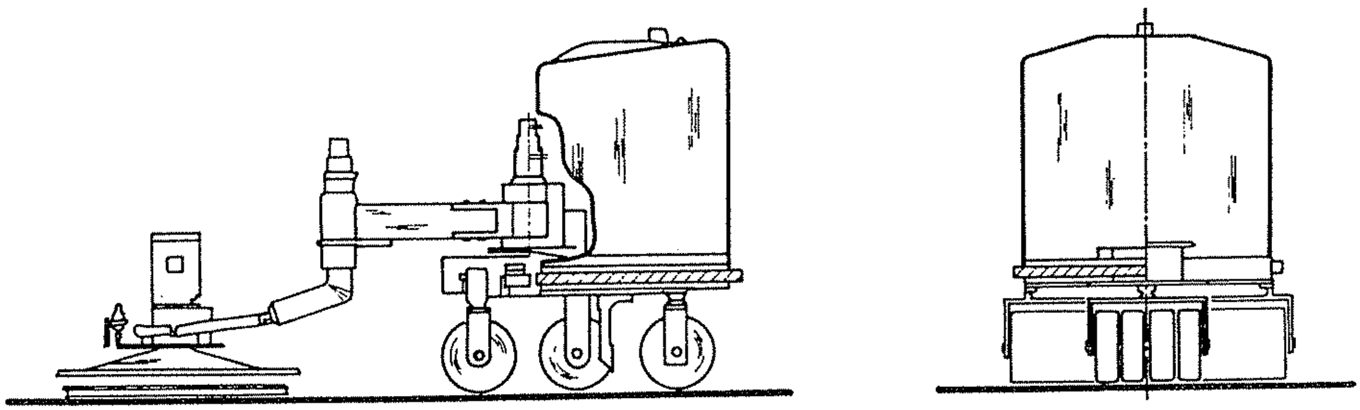


Figure 9 - Concrete Slab Finishing Robot (FLO4) developed by Kajima in Japan. (Redrawn from [34].)



7. WALL SYSTEMS. There are two basic types of wall systems used in structures: load bearing and non-load bearing. The load bearing wall systems are an integral component of the structure and should be considered as part of the building's frame. Non-load bearing wall systems are usually either prefabricated panels or masonry walls.

There have been several efforts to develop robotic equipment to automate activities in the construction of walls. The examples below illustrate the pouring of concrete walls and the installation of prefabricated wall panel components:

- Automatic concrete sprayer (WAL3) developed jointly by two Japanese firms, Taisei Corporation and Kobe Steel Company. The machine is illustrated in the Appendix. Its use would seem to include other activities in addition to to wall construction.

- Concrete Placing Crane (WAL5) developed at Ohbayashi-Gumi (Japan) automates the operation of pouring concrete into wall forms. The use of this machine reduces manual labor time and eliminates the heavy work involved.

- Robotic system, called Trackbot and Studbot (WAL6), for automating certain tasks during the installation of internal prefabricated walls in a building. The system was developed at M.I.T. These two robotic devices are illustrated in the Appendix.

Masonry walls constitute a possible area for the application of construction robotics. Although the bricklaying activity is repetitive, the use of both fluid (mortar) and solid materials (bricks, blocks), and several types of inspection that must be done during the process pose a difficult challenge for a robot.

New standards for brick laying materials and methods is probably the first step towards using robots for bricklaying activity.

8. FINISHING. A multitude of finishing activities can be cited. Finishing includes all of the activities that are needed to complete the structure beyond the first seven construction phases, make it aesthetically appealing and ready for use. The finishing activities include the mechanical and electrical work, application of insulation, installation of windows and caulking, painting, wallpapering, paneling, tiling, and other similar tasks. Some of these activities are similar to those discussed in some of the previous paragraphs.

Generally, precision requirements in finishing tasks are more stringent than in other phases because of aesthetic reasons. For example, the application of a brick veneer facing to a wall is actually a brick laying task that is done more precisely than a regular masonry wall. Some finishing activities require a great amount of skill. For instance, tile finishing is a complex inlaying activity where a series of checks must be done constantly in order to make sure that the tiles are properly aligned in three dimensions.

Robots that would be employed in finishing tasks must be capable of high precision and must utilize sensors to achieve the necessary precision level. Thirteen examples of projects classified as development efforts in finishing robots are presented in the Appendix. They represent a variety of finishing tasks that can be accomplished by robots or teleoperators. Some examples are:

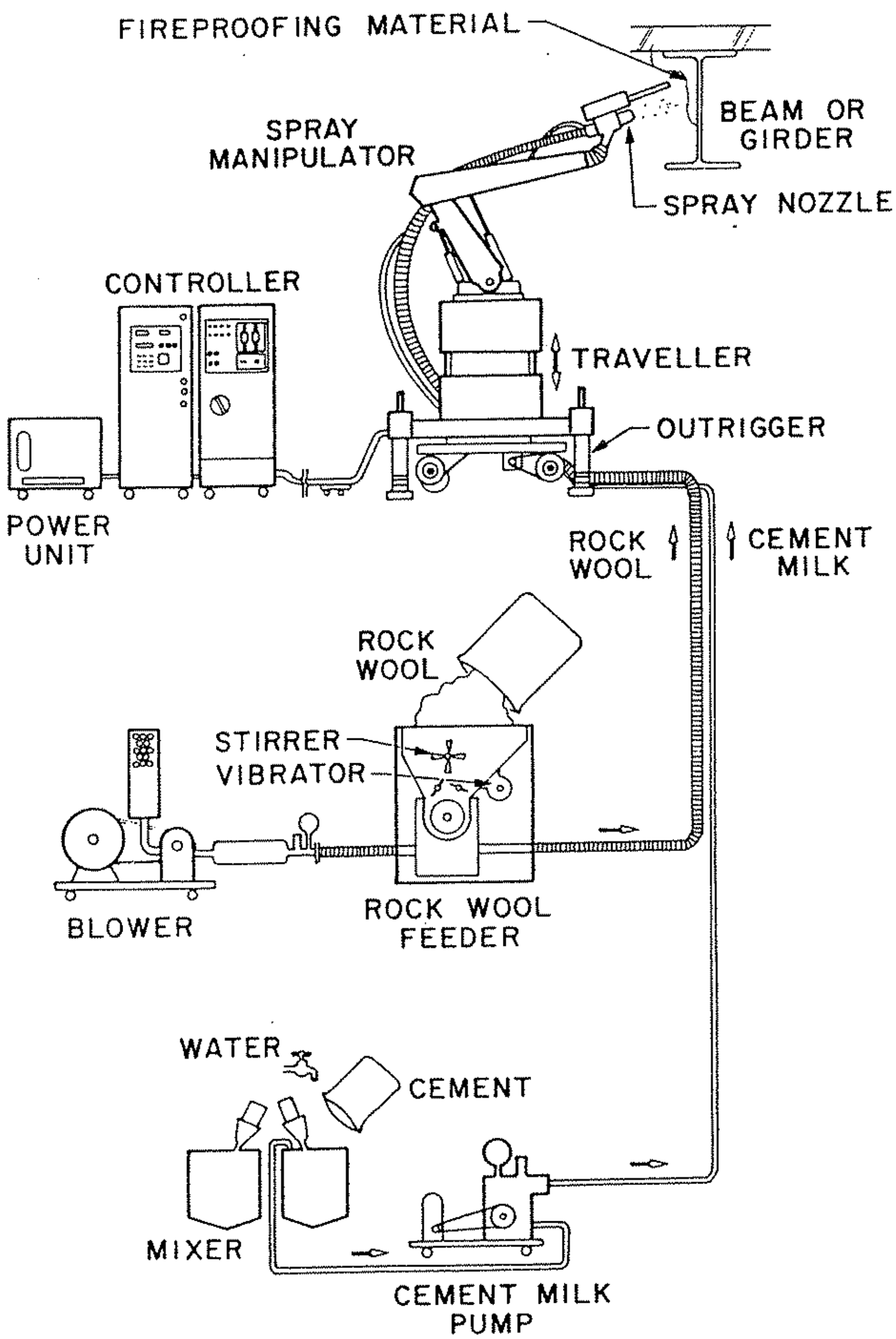
- Shimizu Site Robot (FIN3). This robotic system was designed to spray fireproofing material onto the steel structural members of a building more quickly and uniformly than human workers. A diagram showing the operation of Shimizu's robot is illustrated in Figure 10 on the following page.

- Exfoliated Wall Tile Detectors, developed to traverse exterior walls of buildings and sense loose tiles on the building surface. Two projects were undertaken in Japan, one by Takenaka Komuten Co. (FIN9), and one by Kajima Corp. (FIN10). The Takenaka Komuten Co. (FIN9) wall tile detector is illustrated in the Appendix.

9. DEMOLITION. After a structure completes its useful life span, it becomes necessary to remove it from service and ultimately to demolish it. This is necessary for a number of reasons, including city regulations, efficient utilization of land, and maintenance cost.

Demolition must be done in a safe and organized manner in order to salvage the materials that still have monetary value. This requires different types of tools and equipment during the demolition procedures. Metallic parts are cut or sawed whereas the concrete structure is usually destroyed by explosives or a wrecking ball.

Figure 10 - Diagram of robotic system to spray rock wool on beams and girders during construction (FIN3). (Redrawn from [34].)



Decommissioning of nuclear reactor facilities is a special case of demolition. These structures must be carefully disassembled in order to prevent possible radioactive contamination of the environment. There are also serious hazards to the human workers who perform this demolition. Because of the hazards to human workers, the use of robots is logical objective to pursue.

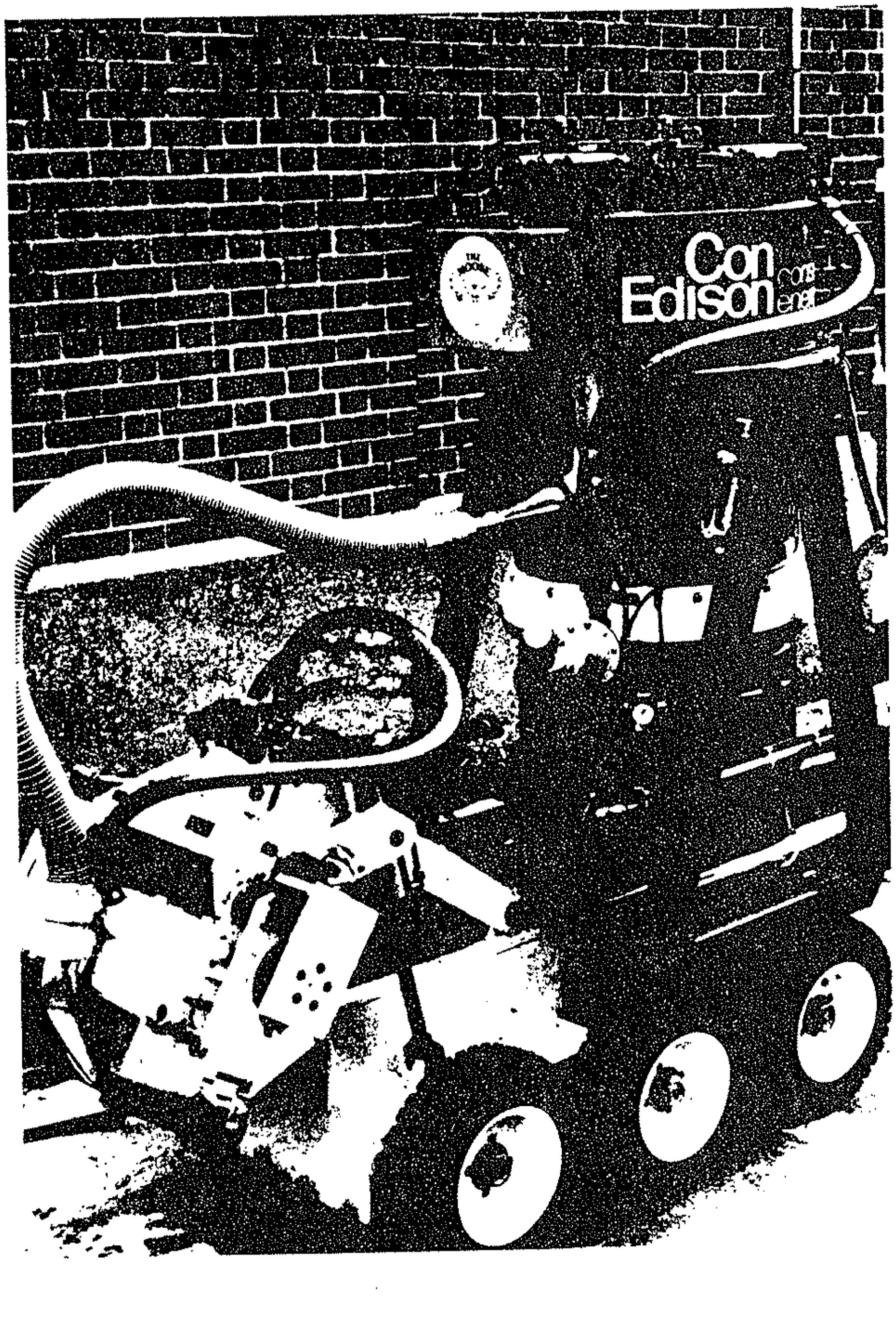
Several robotic systems are being developed for demolition tasks, including several designed for use in nuclear facilities. Six projects were classified in the Demolition (DEM) category and are described in the Appendix. To indicate some of the development activity in this area, three of these projects are presented here:

- Abrasive Water Jet Cutting Robot (DEM1). This system was developed by Kajima Corp. in Japan. It consists of a commercial industrial robot adapted for use with a high pressure water jet nozzle as its end effector. It can be used to cut concrete during demolition activities. The system is illustrated in the Appendix.

- "Moose" Demolition Robot (DEM2), a commercial product by Pentek Inc. illustrated in Figure 11. As shown in the figure, this is a mobile robot designed to perform observations in areas inaccessable to humans, paint removal on walls, and demolition of concrete floor surfaces. The first machine was used at the Three Mile Island Unit 2 containment building in 1984.

- Remote Work Vehicle (DEM6). This robotic vehicle was designed by the Construction Robotics Laboratory at Carnegie Mellon University. It has been used to take radioactive samples from the contaminated basement of the Three Mile Island Reactor Number 2 containment building.

Figure 11 - MOOSE Robot (DEM2) developed and marketed by Pentek Inc. (Courtesy of Pentek Inc.)



DISCUSSION ON MOBILITY AND INTELLIGENCE OF CONSTRUCTION MACHINES

In the previous sections of this report, several characteristics of robotic machines that would perform construction tasks have been identified. Two of the most important characteristics that distinguish construction robots from manufacturing robots are:

1. Mobility - The ability to move about the construction site.
2. Intelligence - The sophistication of the machine's control system to perform complicated construction tasks under autonomous control.

Each of these characteristics can be classified into various categories, each successive category representing a higher level of capability.

Classifications for Mobility and Intelligence

The possible mobility categories range between machines that are stationary and robotic machines that can walk under their own power and guidance. We have defined five levels of machine mobility and these are presented in Table 5.

The intelligence categories are presented in Table 6. The list begins with hand-held and powered tools that are manipulated by human workers to perform some useful function. These tools possess no intelligence. Although hand-held tools and powered tools are equal in terms of intelligence, they can be distinguished according to whether or not a human worker provides the energy to operate them. The highest level of intelligence are cognizant machines that can perform complex tasks requiring skill and judgment without human interference. This category has not been achieved in practice.

- -

Table 5 - Robot Mobility Classes

1. Stationary - Robotic devices in this class do not move about during their operation, and if transported, they usually require a lengthy setup. Most industrial robots operating in factories today exemplify this category.

2. Transportable - These systems are designed to be easily moved between locations. They are not self-propelled.

3. Defined Pathway Vehicles. This class includes vehicles that move along defined pathways. There are two subcategories:

   A. Horizontal Defined Pathway Vehicles - These vehicles move along horizontal tracks or other defined pathways. The vehicles are self-propelled. Automated guided vehicles used in factories and warehouses are examples of this group.

Table 5 - continued.

B. Vertical Defined Pathway Vehicles - These are wall-climbing vehicles which are suspended from cables that cause the vehicles to move along the vertical surface.

4. Rover - This category includes wheeled and tracked vehicles that are self-propelled but not limited to move along defined pathways. Rover vehicles therefore either require human operators to control their movement during operation, or they must be provided with a high level of autonomous control in order to determine their own routings.

5. Walker - These are vehicles with legs whose primary form of locomotion is walking. In order to operate autonomously, walker vehicles generally require a more sophisticated level of control than Rovers because of their inherent lack of stability in the use of legs instead of wheels.

- -

Table 6 - Equipment Control Sophistication

1. Manually Controlled Tools - This category includes tools that are manipulated by human workers. There are two types:

   A. Hand-held Tool - This type consists of simple non-powered tools such as screwdrivers and hammers which require no automated controls. The human worker provides the energy to operate them.

   B. Power Tool - Tools such as a hand-held power drill or jackhammer. The operator guides the action of the equipment.

2. Teleoperated - Equipment is controlled by a human operator from a remote location. The operator observes the operation of the equipment and transmits control instructions.

3. Programmable - Machinery with an on-board processor or computer link capable of performing a preset series of movements. Examples include numerically controlled milling machines and automatic concrete mixers.

4. Autonomous - A system which can perform tasks without intervention, assuming the environment encountered is that for which it was designed.

5. Cognizant - Systems in this class can formulate strategies or plans, carry out tasks without intervention, monitor their own performance, react to changes in their work environment, and possibly learn from their work experiences.

- -

There are three considerations about these lists of mobility and intelligence characteristics that should be noted. First, the categories presented in the respective tables are oriented towards robotic devices that would perform construction tasks. A corresponding list prepared for tasks other than construction might contain a different set of categories for the two characteristics. Second, some of the categories in the two tables represent capabilities that are not yet available on commercial machines. We nevertheless include them in the list because we anticipate that future machines will possess these features. Finally, there exists a general correlation between machine mobility and intelligence. Machines that are more mobile require more intelligence in order to move successfully.

How Mobility and Intelligence Relate to Construction Robotics

The following paragraphs analyze these mobility and control characteristics in relation to the various robotic construction projects identified in the preceding section as well as currently available construction equipment in widespread use today.

Most of today's commercially available construction equipment falls into the mobility category of being either stationary or transportable, and into the intelligence category of being manually controlled. For example, a power drill or a hand-held concrete floor finisher are both manually controlled portable tools, while a tower crane is a manually controlled stationary piece of equipment. A programmable or reprogrammable sequence of speeds or motions of these devices is not present. This programmability feature is a requirement for the equipment to be classified as robotic.

The application of servocontrolled equipment within the construction industry seems to be quite limited, for example for speed regulators on engines and elevators. A common application of servocontrol systems in industrial robotics is to cause the end effector of the manipulator to follow a trajectory or predefined contour. For example, the robot might be controlled to follow a straight line path between two points in the workspace. Rather recently, servoactuation has progressed from end effector motions to the application of forces and torques between an end effector and a part. For example, the gripper is controlled to apply a certain level of grasping force appropriate for the object being handled. The design and use of these highly sensored end effectors is currently a topic of much interest within the robotics community. By using predefined force or motion trajectories and appropriate servocontrol algorithms, it is possible to improve the performance of machines to perform various automated tasks. It is likely that these kinds of systems will be applied in construction machinery in the future.

Teleoperated manipulators are utilized in hazardous environments. There are several examples given in this report of their use for working in radioactive environments (SUR3), (SUR11), (DEM6), and DEM7); in underwater activities (SUR6), (SUR12); and in high electrical power environments that would be dangerous to human workers (FIN11). In these cases, an operator moves a joystick or other device in the way he/she wishes to have the robot end effector move.

A refinement of the teleoperated device involves the use of feedback of the force between the robot end effector and work to the operator. Using feedback in this way, the manipulator can be made to operate in a more human like fashion by the operator.

Tower cranes have many of the features of teleoperated manipulators. One of the differences is that the individual joints or actuators of the tower crane are controlled by means of separate joint levers. In the operation of most remote manipulators, coordinated control of the arm is usually provided by means of joysticks that control multiple joints simultaneously.

When a teleoperated device is used to perform a motion pattern that is highly repetitive, consideration can be given to the use of programmable control. In this level of control sophistication, the device repeats the sequence of motions automatically rather than under human guidance. The programmable machine is first "taught" the motion cycle by the human programmer, with the cycle being recorded into controller memory. Then the controller plays back the program, causing the motion cycle to be executed under automatic control. The Robot Tower Crane by Takenaka Komuten (FRA10) is an example of a machine that can be operated either in a teleoperated mode or in a programmable "teach-and-playback" mode.

Among the robots classified as stationary are applications to drilling, riveting, welding, maintenance, and drydocking. The drilling, riveting, and welding robots are primarily industrial robots which could potentially be adapted to the construction workplace. The projects undertaken by Lockheed-California (FIN6) and General Dynamics (FIN7) are representative of this category. Currently, these robots require the structured environment of the factory, and it has not been within the scope of this survey to consider these types of robots. There are examples where the flexibility and adaptability of these robots is being increased, for example through the use of interchangeable tooling and increased mobility. These enhancements may lead to applications in construction.

Some of the larger construction projects, like the Alaskan Pipeline, have required the use of vehicles to move workers and materials to, from, and within the construction site. Even in smaller construction sites, vehicles are used for excavation and for moving materials to and within the construction site. The current practice is to control these devices manually. Let us examine some of the progress that has been made in increasing the level of mobility of equipment used in construction.

Transportable robots have been developed for applications to drilling, heavy material placement, and grading. Mightly Jack (FRA9) is an example in this category. The End Effector for Robotic Drilling (FIN7) is transportable in the sense that the vehicle to which it is attached need not be robotic, it could be manually operated, therefore the robotic device is transportable. The TOMCAT (FIN11) is another example of a transportable manipulator, in this case a teleoperated machine. In these and other systems in this class, the robotic or teleoperated device is mounted on a mobile vehicle which is usually manually controlled.

A large degree of mobility has been given to the wall climbing robotic devices (FIN9), (FIN10), although their control sophistication is rather primitive. These devices typically move over large planar vertical surfaces by being tethered to the underlying structure. The control is similar to that of an elevator or at most a simple teleoperator afforded by the rectilinear geometry.

Machines that follow defined pathways include the Shimizu Site Robot (FIN3) and the Abrasive water jet cutting robot (DEM1). Both of these robot systems are comprised of conventional industrial robots mounted onto a mobile platform to perform their tasks.

The current level of technology allows for the use of teleoperated rovers in moderately structured environments such as the basement of TMI-2 containment building (SUR3), (DEM6), (DEM7), and the use of autonomous rovers in highly structured environments such as tunnels (SUR1), (SUR8). In both cases the sensor interaction between the rover and the environment is a central issue. In many cases, the computational effort to reduce sensory data into a form usable by the servoactuators of the rover is substantial.

The Concrete Slab Finishing Robot (FLO4) is more autonomous in its movements, with the capacity to determine its own position and make adjustments to its path. The Concrete Floor Finishing Robot developed by Takenata Komuten (FLO5) and the multi-purpose travelling vehicle by Shimizu (FIN8) also seem to possess this capacity for autonomous movement. Another project in this category is the Autonomous Land Vehicle at Carnegie Mellon University (SUR7).

In the case of walking robots (SUR5), (SUR6), (SUR10), (DEM5), the computational burden greatly increases because appendage control and balancing algorithms are required in addition to the navigation and mapping required of the rovers.

It is anticipated that the mobility and control features which characterize many of the robotic projects described in this report will become more and more common on future construction equipment.

CONCLUSIONS

1. There are important reasons for the use of robotics technology in construction. These reasons include international competitiveness, productivity, safety, and quality.

2. The characteristics of construction work that would have to be addressed in the development of robots operating at the construction site include:

   a. Hazardous to humans. Construction tasks are often hazardous to humans. By substituting robots in place of humans in the most dangerous work, safety is improved.

   b. Repetitive tasks. Many construction activities involve the repetition of the same or similar work cycles. A robot can be readily programmed to perform repetitive work cycles.

   c. Mobility. Construction workers must usually move about the construction site. Robots would have to be provided with the capacity to move or be readily moved.

   d. Intelligence. Construction robots would operate in a less structured environment than industrial robots in manufacturing applications. A higher level of machine intelligence would be required. This includes greater use of sensor technology and decision-making capability.

3. Construction robotics technology has developed more rapidly in Japan than in the United States. Of the 61 projects identified in this report, nearly 58% were conducted in Japan, while 39% were carried out in the United States. (The remaining three per cent were of European origin.) The Japanese construction industry is more willing to experiment with and participate in the development of this technology than its U.S. counterpart. There are several instances in which multiple research efforts are taking place at different companies to develop technology for the same application area. Concrete placing cranes, handling and distribution of concrete at the work site, and wall tile detectors are examples of these multiplied efforts. The Japanese are therefore competing amongst themselves to develop construction robots. This competitive environment is probably a condition that will accelerate the development of robotics technology in their country.

4. Current developments in construction robotics have lead to machines that are designed to perform very specific tasks. The prototype machines have been custom-made and are very expensive. They can perform only one or a limited number of tasks. It would be desirable for future commercially available construction robots to be designed to be general purpose, with the opportunity to define the specific application through the use of different types of end effectors.

5. Mobility and intelligence have been identified as two areas where advances must be made in the technology of current industrial robots in order to apply these types of machines in construction work. Based on the research and development efforts in construction robotics documented in this report, these two features are interrelated to some degree.

6. Generally, the construction robots developed thus far do not possess the accuracy and repeatability capabilities that manufacturing robots possess. Currently, the construction tasks they are being called on to accomplish do not require the high accuracies that most manufacturing jobs require. Excavation robots, concrete distribution robots, automated cranes, and demolition robots are all examples of tasks that do not usually require high precision. There are other construction tasks (e.g., making connections, certain finishing tasks) in which a much higher level of accuracy and precision will be required by future construction robots.

APPENDIX - Survey of Projects in Construction Robots

Each entry contains the code, the name of the robot or project, the name and location of the organization responsible, and a brief explanation of the robot's capabilities. The codes correspond to the construction phases defined in Table 4 in the body of the report. The code symbols are interpreted as follows:

- SUR - Surveying
- EXC - Excavating and grading
- FOU - Foundation
- FOR - Formworks
- FRA - Framing
- FLO - Floor systems and roofing
- WAL - Wall systems
- FIN - Finishing
- DEM - Demolition

Surveying (Symbol: SUR)

SUR1 Snake-like Arm

Toshiba Nuclear Group, Japan

This is a teleoperated device used for inspecting pipes and similar small areas with limited access. It consists of an articulated arm that can reach through a hole and proceed through a labrinth of pipes to inspect areas that are difficult to reach. The arm carries a TV camera on the end, and is controlled by on operator watching the TV image. The operator controls the motion of the camera by simply pointing it in the desired direction. A computer monitors the trajectory of the path, and causes the arm to assume the shape of the trajectory so that it can avoid obstacles as it snakes its way through the restricted space. [1], [2]

SUR2 Seabed Monitoring Robot

Kokusai Denshin Denwa, Japan

This robot monitors seabed conditions before, during and after submarine cables are laid. The system is set to be used in the repair and maintenance of submarine cables between Japan and China. [5]

SUR3 Remote Reconnaissance Vehicle (RRV)

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

The RRV is a rigid, six-wheel drive teleoperated machine whose missions have included visual inspection, radiation mapping, and sludge sampling in the basement of the TMI-2 containment building. The RRV typically carries three cameras and lighting, it is linked to its control console via a thin, flat ribbon umbilical cable that conveys power, control signals, and video telemetry. The machine is illustrated in Figure 5 in the body of the report. [44].

SUR4 Remotely Controlled Vehicles

(Manufacturer unknown), West Germany

These are radio controlled robots about the size of a small car which carry television cameras and radiation sampling equipment. West Germany has been using maintenance robots in nuclear power plants for nearly a decade and includes special robots in its task force for handling nuclear plant emergencies. [27]

SUR5 Adaptive Suspension Vehicle

Ohio State University, Columbis, Ohio, USA

This project is concerned with the development of a six-legged walking robot, under support from the Defense Advanced Research Projects Agency (DARPA). The vehicle is equipped with a cockpit, from which a human driver can control the vehicle's direction of motion using a joystick. Its forward motion resembles that of an insect, while its sideways motion mimics a crab's motion. Maximum speed is 8 miles per hour. The machine is equipped with a gyroscope for balance, laser vision, sonar, and force sensors in its feet. Eventually, the designers expect the machine to be capable of autonomous movement. [6]

SUR6 ReCUS (Remotely Controlled Underwater Surveyor)

Komatsu, Ltd., Japan

ReCUS is an 8-legged walking robot which shows great mobility and stability on uneven grounds. This robot can even move on grounds that are too uneven for crawler machines. In addition, it is highly stable against reaction forces in the working environment (e.g., water resistance). Owing to this feature, it is applicable to a wide range of underwater construction activities. [17]

SUR7 Autonomous Land Vehicle Project (Terragator)

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

The goal of this project was to develop vision and intelligence capabilities for a mobile robot operating in the unstructured world outdoors (as opposed to a laboratory environment). The Terragator (Terrestrial Navigator) is a six-wheeled vehicle 64" long by 39" wide by 37" tall. The research vehicle is equipped with a sonar ring, a color camera, and a laser range finder. Its initial task is to follow roads and sidewalks, while avoiding obstacles such as trees, humans, and traffic. The fact that the vehicle itself provides a mobile platform, power, video link, and two-way radio with a remote computer makes it easy for researchers working with different sensor packages to interface their choice of sensors, processors, and communications in order to run various experiments. [18]

SUR8 "Kluge" Mobile Inspection Robot

Cybermation, Inc., Roanoke, Virginia, USA

This is a radio-controlled, three-wheeled vehicle that can navigate extremely narrow passageways. Because of its narrow profile, it is considered to be an attractive platform for a construction robot working in building interiors. [27]

SUR9 "Surveyor" Inspection Robot

Automation Technonology Corp., Columbia, Maryland, USA

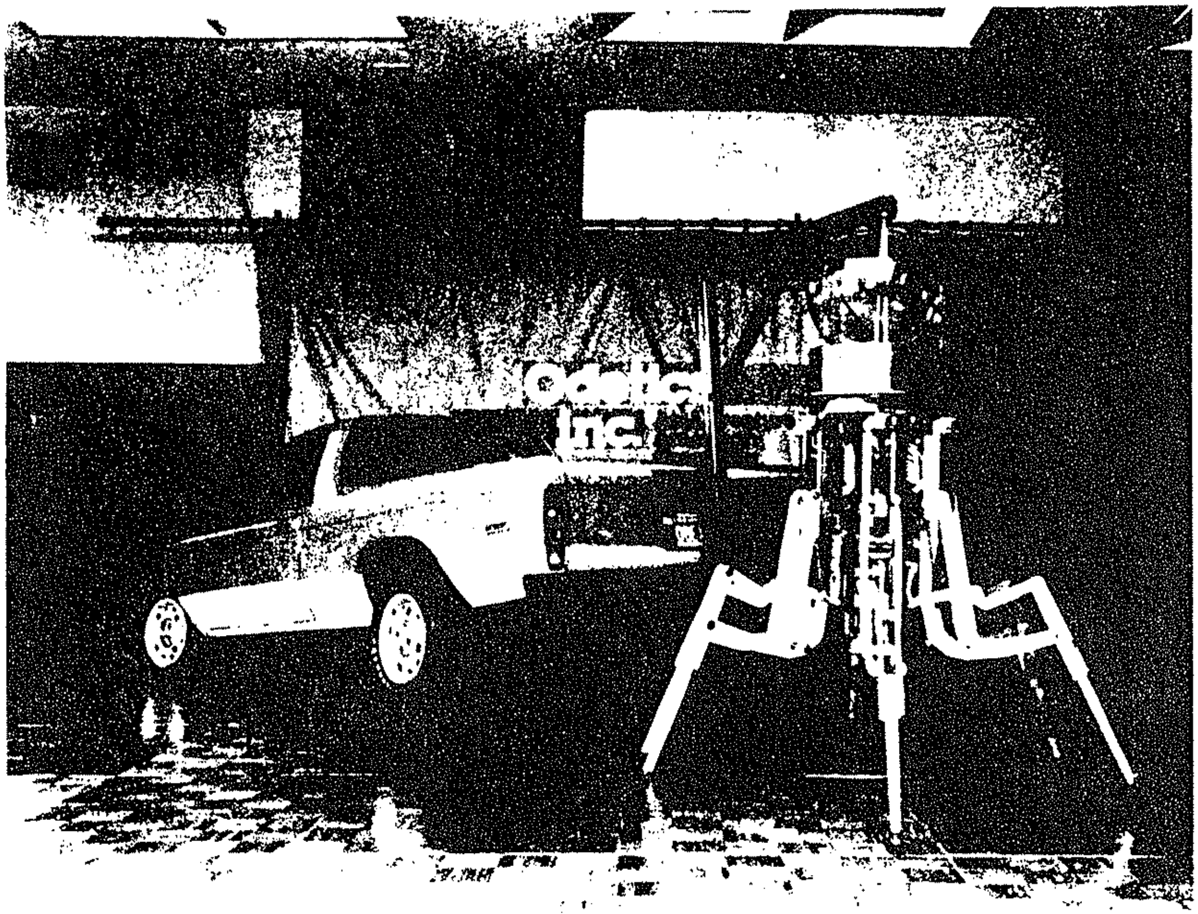
This robot can be operated in water up to 6 inches deep and maneuver through openings only 32 in. tall. [27]

SUR10 Odex I

Odetics Inc., Anaheim, California, USA

The Odex I is a commercially available six-legged walking robot built by Odetics Inc. It was first introduced in March 1983. According to the Odetics marketing announcement, this machine "can change profiles and direction to suit environmental requirements, traverse uneven terrain, climb or descend while maintaining a stable platform, lift objects many times its own weight, walk while lifting and performing useful work using up to three of its six articulators." It is designed to be a suitable platform for applications in military, nuclear power, mining, agriculture, and other areas. The Odex I is illustrated in Figure 12. [22]

Figure 12 - ODEX I, a walking robot platform developed by Odetics Inc., shown here lifting the rear of a small truck (SUR10). (Courtesy of Odetics Inc.)



SUR11 Advanced Integrated Maintenance System

Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

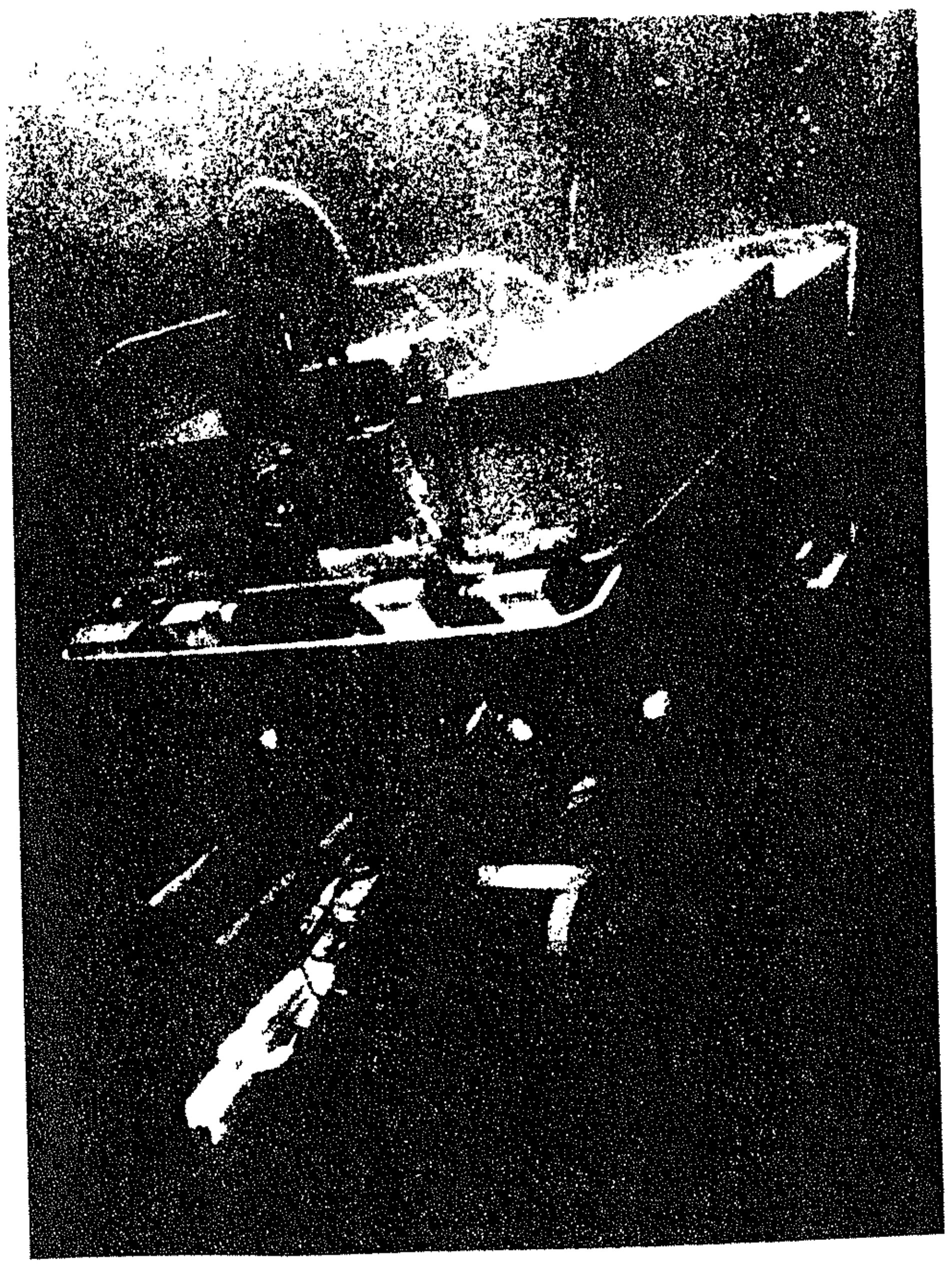
This program focuses on developing a remotely controlled maintenance system for fuel reprocessing tasks. It is a teleoperated system that includes slave arms which are moved about the fuel reprocessing cell on a transporter gantry. The arms are designed to function in an environment which contains high levels of radiation and surface contamination. Through the use of television cameras and force feedback, the operators control the movement of the arms. One of the major goals of this project is to decrease the exposure plant personnel radiation through the use of remote maintenance equipment. [15]

SUR12 Cable-controlled Underwater Recovery Vehicle (CURV)

Naval Underwater Systems Center, Newport, Rhode Island, USA

The United States Navy has a number of applications for underwater vehicles, many of which are operated as unmanned devices. An example is the Cable-controlled Underwater Recovery Vehicle shown in Figure 13 in an official photograph of the U.S. Navy. Note the gripper projecting from the front of the vehicle. This is used for grasping articles underwater under control of a surface vessel to which the CURV is connected by means of an umbilical cord. [12]

Figure 13 - Cable-controlled Underwater Recovery Vehicle (SUR12). (Official Photograph U.S. Navy.)



Excavating (Symbol: EXC)

EXC1 Underwater Rubble Levelling Robot

Komatsu, Ltd., Japan

This robot is employed in harbor construction. The system is said to be 20-40 times more efficient than a conventional system using divers. [9]

EXC2 Generex - Second Generation Robotic Excavator

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

The purpose of this development project is to design a cognitive system for General Robot Excavation. The system will improve the earlier REX (Robot Excavator) which integrated sensing, modeling, planning, simulation and action specifically to unearth buried utility piping. REX uses a supersonic air-jet cutter to dislodge material without direct contact. The human interface consists of a joystick, keyboard, and an animated display. The actuation hardware consists of a four-link backhoe, mounted to a utility truck. [45]

EXC3 Underwater Bulldozer

Komatsu Co., Japan

This was described as a machine that operated underwater. Detailed information was not available at time of report preparation. [9]

EXC4 Robot Jumbo

Kumagai Gumi Co., Ltd., Japan

This is a large, automated and robotized hydraulic rock drilling machine. [9]

EXC5 Drilling Robot

Kajima Corp., Japan

This robot holds hole patterns for excavation in its memory and operates automatically with a mechanized 5-arm jumbo excavator. The automatic excavation machine was developed for the purpose of increasing the excavation speed regardless of worker skill and maintaining a flat, smooth surface without over-excavation. The machine is positioned on the surface and then repeats the excavation procedure in accordance with the pattern in its memory. [34]

EXC6 Shield Driving Automatic Control System (SDACS)

Hazama-Gumi Co., Ltd., Japan

The SDACS is a machine used in the digging of tunnels. The operation involves the driving of a shield into the earth to define the direction of the tunnel. The shield supports the cutting head and prevents earth and water at the working face from falling into the finished tunnel. The SDACS controls the direction that the shield is driven into the earth. The shield is driven by hydraulic jacks which push against the tunnel liner. The position of the shield is measured by a laser and compared against the desired path of the tunnel which is stored in computer memory. The error signal is used to control the hydraulic jacks so as to servo the tunnel boring machine to the desired path. There are thirty jacks spaced evenly around the periphery of the shield. The computer selects which combination of these to pressurize so as to drive the shield for the next sampling period. This system keeps the center line of the tunnel within 10 mm of the design specification. [1]

EXC7 Lagoon Pumping System

Liquid Waste Technology, Somerset, Wisconsin, USA

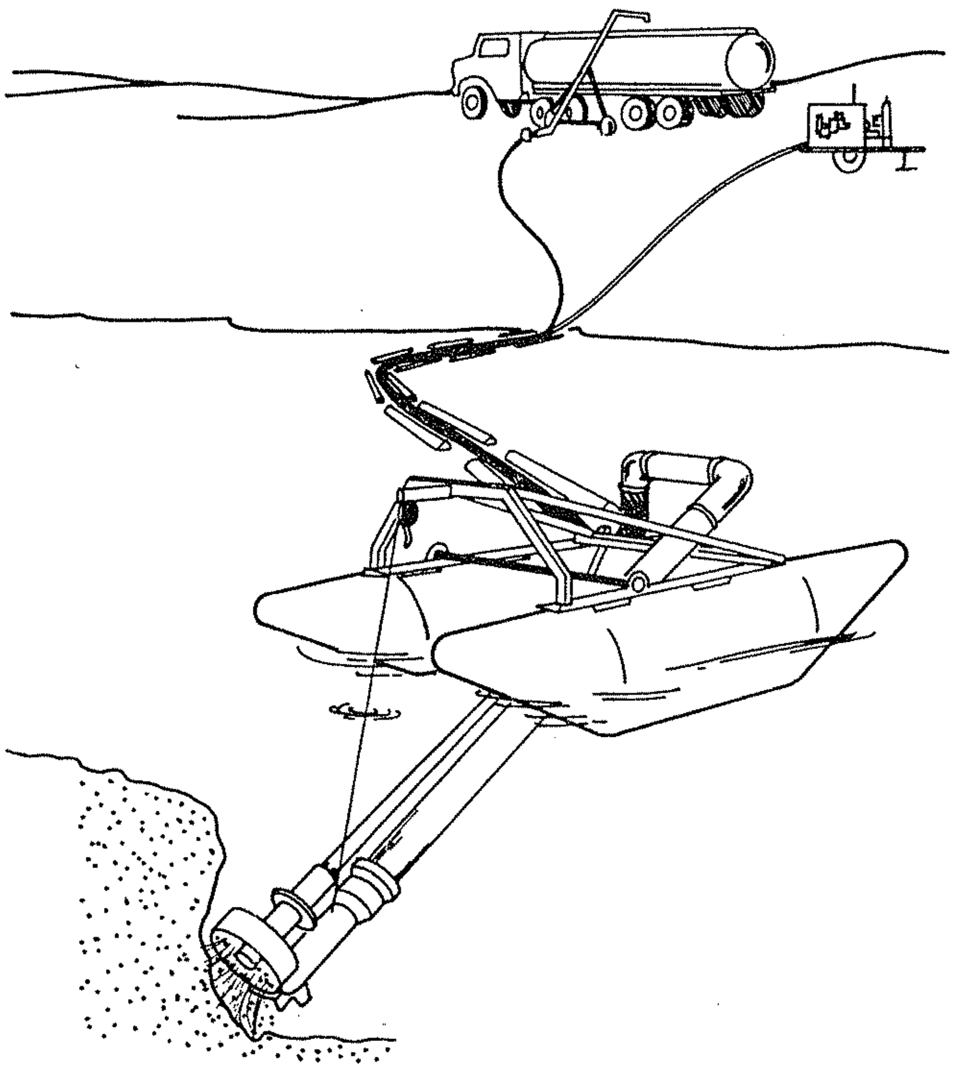
This is a commercial product, illustrated in Figure 14, designed for unmanned operation to remove sludge and sand from below the surface of the water. It is included here because it is essentially an excavation operation performed underwater. As the figure indicates, the floating platform removes material from the bottom of a lagoon or other water body. An on-shore truck is used to collect the debris from the platform. Hydraulic power is provided by an on-shore power unit. Various other products by Liquid Waste Technology are designed for similar underwater operations. [19]

EXC8 Laserplane Grade Control System

Spectra-Physics, Mountain View, California, USA

This device is not a robotic machine; it is a sensor and control device that uses a laser beam to control the height of a bulldozer blade, permitting day or night operation of the equipment. The system also reduces the manpower required for surveying and facilitating grading operations. [28]

Figure 14 - Lagoon pumping system for removing sand and sludge from shallow waterways (EXC7). (Redrawn from marketing materials supplied by Liquid Waste Technology Inc.)



<u>Foundation</u> (Symbol: FOU)

None of the construction robotics projects could be classified uniquely into this category.

Formworks (Symbol: FOR)

There were no projects identified that could be classified uniquely in this category. Some of the Frameworks projects (following category) might be used to perform Formworks tasks.

Framing (Symbol: FRA)

FRA1 Robotic Assembly for Mobilization Construction

U.S. Army Construction Engineering Laboratory, Champaign, Illinois, USA

This R&D study is concerned with the potential opportunities for using robotics to assist in the rapid construction of numerous wood framed buildings during a mobilization. Robots have been identified for use in several activities including the following: wood framing, painting/spraying, site work, concrete work. The development of a portable robotic factory for rapid building component production was also reported. [10]

FRA2 Bolting Robot

Kajima Corp., Ltd., Japan

Detailed information was not available at time of report preparation. [9]

FRA3 Stud welding robot

Kajima Corp., Ltd., Japan

In the construction of nuclear plants, large numbers of devices, reinforcing bars, ducts, etc. are embedded into the concrete. In order to place these devices, stud dowels must be welded to the reinforcing bars in the concrete. The welding of the numerous stud dowels to the reinforcing bars is very time and labor consuming. This stud welding robot developed by Kajima can execute this work efficiently. The number of workers is reduced from three to two and their working posture is improved. [34]

FRA4 RW-250 Arc-Welding robot for large steel construction

Misubishi Electric Corp., Japan

This robot possesses a six-axis articulated arm attached to a two-axis unit. A sophisticated algorithm has been developed to provide maximum operating flexibility to the welding torch controlling eight axes simultaneously. Intelligent functions including an arc weaving sensor and a wire touch sensor are incorporated into the algorithm to compensate for misalignment and/or inaccuracy of workpieces. A program editor for large workpieces is available and welding macro instructions facilitate the programming. [14]

FRA5 The Adaptive Robotic Welding System

Fairbanks Weighing Division, Colt Industries, Meridian, Missipi, USA

This is a continuous arc welding robot system. The welding of parts in excess of 8,000 lbs, requiring up to 7,600 inches of weld has been accomplished through the adaptive location of weld start point and seam tracking. Parts traverse between the legs of a large rectilinear robot on air pallets with a simple guidance track. Part cycle times range from three minutes to nine hours. The system has no limit with regard to heat or radiation which allows use of previously intolerable optimum welding parameters. This automated system obtains 70% "arc on time" as compared to 20 to 30% arc on times that are typical for manual operation. One final advantage of this system is that valuable welding knowledge for individual parts can be retained in the welding program so that reliance on key personnel is reduced. [4]

FRA6 Rebar Placement Machine

Takenaka Komuten Co., Japan

This machine can handle a rebar up to 15 meters in length and place it vertically within 10 cm of programmed position. It is capable of carrying loads up to 1000 kg within a 6 meter radius work envelope. It was originally developed to be used in nuclear construction work. [9]

FRA7 Heavy Rebar Arranging Robot

Kajima Corp., Japan

This robot can carry 20 reinforcing bars and travel on the previously laid bars, placing the new ones automatically at prearranged intervals. The robot moves the bars to the right and left, shifting the position of the joints to form a zigzag or radial arrangement. With a change of arms, the robot can also perform vertical and horizontal placement of reinforcing bars for walls. This robot can reduce labor costs by 40 to 50 percent. Also, the total time for arranging reinforcing bars is cut by 10 percent. [34]

FRA8 Robotic Crane

National Bureau of Standards, Gaithersburg, Maryland, USA

Basic work on automating the operation of construction cranes is currently underway at NBS. Their system consists of a platform suspended by wires that can be manipulated from above to permit controlled movement of the platform in six degrees of freedom. The platform can be used to mount a robot or manipulator to perform various construction tasks. [3]

FRA9 Mighty Jack steel assembly robot

Shimizu Construction Co., Ltd., Japan

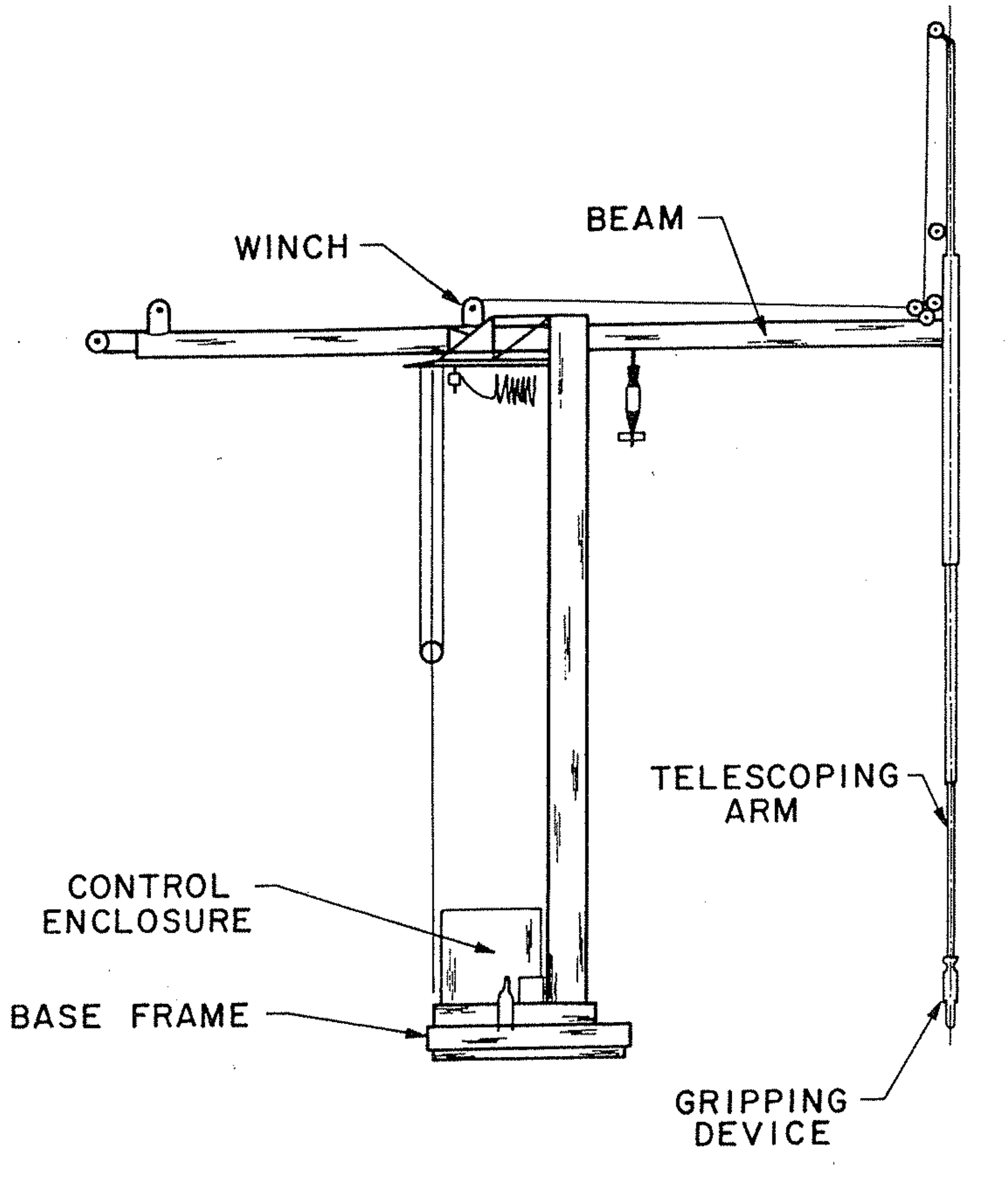
The "Mighty Jack" is a large manipulator designed to lift steel beams and position them during construction. When lifting beams, the manipulator itself is hung from a tower crane. This operation is illustrated in Figure 7 in the body of the report. During the positioning operation, the manipulator is temporarily attached to the tops of two parallel vertical columns. It is therefore detached from the tower crane, allowing the crane to be used for other jobs while the Mighty Jack is performing positioning work. A combination of fixed sequence control and remote teleoperation are utilized to control the cycle of operation. Benefits attributed to the Mighty Jack include greater safety and more rapid assembly work. In addition, noise from tapping the jig to adjust bolting holes is eliminated. [34]

FRA10 Robot Tower Crane

Takenaka Komuten Co., Japan

This semiautomatic crane is designed to lift and position steel reinforcing bars for concrete buildings such as nuclear power plants. As illustrated in Figure 15, the device consists of a tower attached to rotating base, a horizontal boom, and a vertical telescoping arm. This configuration provides the machine with a 10 meter working radius, a 15 meter vertical travel, six degrees of freedom, and a lifting capacity of 150 kg. It can be operated manually or in an automatic teach-and-playback mode. The robotic crane operates by picking steel reinforcing bars from an automatic feeder, lifting and positioning the bars to be tied in the proper location by a human worker. In this manner a frame of steel can be quickly constructed. The use of this robot crane has reduced the manpower required for reinforcing bar placement from a crew of seven to three. The crane can be dismantled, relocated, and set up again in about one hour. [1]

Figure 15 - Robot tower crane developed by Takenaka Komuten in Japan (FRA10). (Redrawn from [1].)



FRA11 Heavy Material Lifter

Takenaka Komuten Co., Japan

Detailed information was not available at time of report preparation. [9]

FRA12 Auto Clamp

Ohbayashi-Gumi Ltd., Japan

This is a crane whose function is to release the cable from a steel column at remote high elevations using a wireless remote device. The attachment has been used at several sites for steel column assembly work. The attachment is suspended from the hook of a tower crane. First, a pair of magnetic devices with a shear pin are attached to the top of steel column. After the column is set in place, the attachment is magnetically released from the column by means of FM teleoperation. [34]

Floor Systems (Symbol: FLO)

FLO1 Horizontal concrete distributor

Takenaka Komuten Co., Japan

This machine, illustrated in Figure 8 in the body of the report, is used to apply wet concrete mix to the floor of a steel frame structure under construction. In operation, the machine is fixed to steel column and is guided by a human operator. The articulated arm has four joints and is 20 meters in length when fully extended. From its fixed position, it is capable of covering an area up to 1000 sq m. The concrete is pumped out through the articulated arm and vibrated with rods mounted on the arm. The operator can ride on the end of the arm or use a remote control box to control the movement of the arm. The machine can be detached from the column of one floor and moved to the next floor to distribute concrete to each floor within the steel structure. [34], [35]

FLO2 Concrete laying robot

Taisei Corp., Japan

This is a concrete laying robot that has the ability to control the position of the hose, the amount of concrete being applied, and to prevent collisions between the hose carrying mechanism and the existing building structure. [1]

FLO3 CONDIS Crane

Takenaka Komuten Co., Japan

This is another concrete distributing robot developed by Takenaka Komuten. By contrast to FLO1, this system is designed to distribute concrete on the top deck of a building or other structure, rather than on the internal floors of the building. The articulated arm uses two joints that allow the arm to flex vertically. The CONDIS Crane can also be used as a jib crane by locking the positions of the two joints with pins. [35]

FLO4 Concrete Slab Finishing Robot

Kajima Corp., Japan

This robotic machine is illustrated in Figure 9 in the body of the report. It is designed to finish concrete floor surfaces after pouring the concrete. The work is normally performed by workers who must assume a crouched position to do the finishing work. This tends to be exhausting. As the diagram shows, the machine has wide wheels that permit operation on concrete that has not yet hardened. It is equipped with gyrocompass, travel distance sensor, and self-navigation logic that enables it to determine its position and make automatic adjustments to its path. It is claimed that the machine reduces the number of night shift workers required and achieves quality equal to that provided by skilled workers. [34]

FLO5 Concrete Floor Finishing Robot

Takenaka Komuten Co., Japan

This robot is a small tracked bulldozer that uses eight rotating trowels to smooth the surface of a concrete floor as it moves. The pressure of the trowels is automatically adjusted to the hardness of the concrete, and a TV camera is used to inspect the flatness of the finished surface. The robot uses a laser leveling instrument to control the height of the blade and an automatic navigation system to control the path. It also possesses a collision prevention system. The machine is capable of both rough and fine finishing of the floor surface at the rate of about 100 sq meters per hour. [1], [35]

<u>Wall Systems</u> (Symbol: WAL)

WAL1 Concrete Distributing Robot

Takenaka Komuten Co., Japan

This robot rapidly distributes fresh concrete, with less manpower. The number of workers required is reduced from 15 to 10 in actual use. This system reduces the heavy work that must be performed by workers, improves the quality of concrete slab reinforcement, and speeds distribution of the slabs. [34]

WAL2 Automatic Concrete Sprayer

Kajima Corp., Japan

This concrete sprayer controls the concrete spraying operation using density and concentration of concrete as control variables. The quantity discharged is determined by the amount of air and air pressure and the quantity of accelerator added. The system is computer controlled, so concrete spraying can performed without a technician. [34]

WAL3 Automatic Concrete Sprayer

Taisei Corp. and Kobe Steel Co., Japan

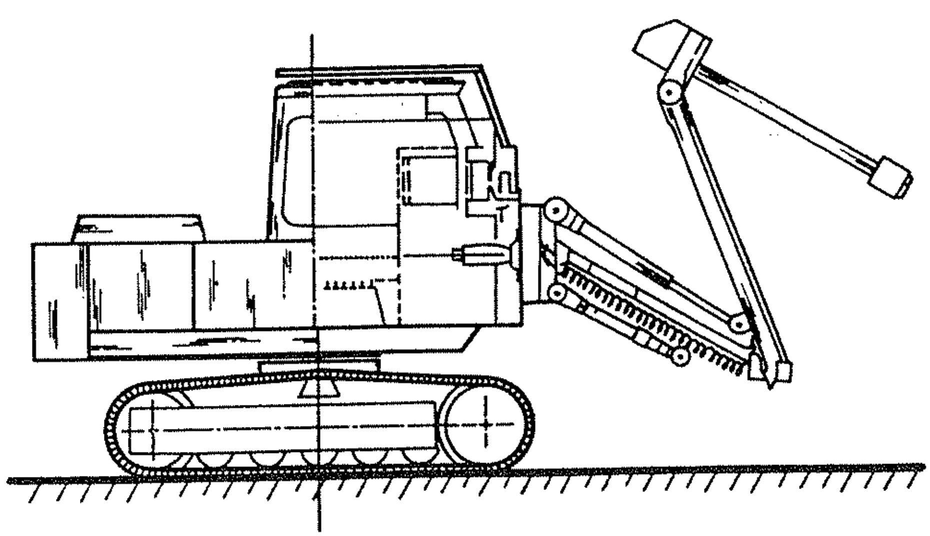
This is another concrete spraying machine that controls the setting of the spray nozzle to the optimal position. The quality of sprayed concrete is thus better than that done by other manipulators. A sketch showing the machine's configuration is presented in Figure 16. [34]

WAL4 Brick Laying Robot

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

This was a project at CMU undertaken to develop a bricklaying robot. Preliminary results were not encouraging and the project was not continued. [46]

Figure 16 - Automatic concrete spraying machine developed by Taisei Corp. and Kobe Steel (WAL3). (Redrawn from [34].)



WAL5 Concrete Placing Crane

Ohbayashi-Gumi Ltd., Japan

This machine has been developed to automate concrete placement, in particular for pouring concrete into wall forms. In additional it functions as a crane. It is composed of four booms which are driven and controlled by a hydraulic servo. Its operation is very easy, even in the manual mode. It provides the following benefits: a) Rapid concrete pouring into wall forms, b) Elimination of dirty heavy work, c) Prevention of misplacement of reinforcement bars by workers, d) Reduction of concrete placing labor costs, e) High efficiency and adaptability as construction equipment. [34]

WAL6 Trackbot and Studbot

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

This is a robotic system for automating certain tasks involved in the installation of straight internal walls in a building. The system includes two separate machines, Trackbot and Studbot. Trackbot is used for positioning and fastening the wall track to the floor and ceiling. It consists of two independent track positioning systems, an upper system for the celing and a lower system for the floor. Track sections are contained in bins to be handled by the positioning systems. The Trackbot system is illustrated in Figure 17 (a). Studbot is designed for positioning and fastening vertical studs between the ceiling and floor tracks installed by Trackbot. It is shown in Figure 17 (b). [8]

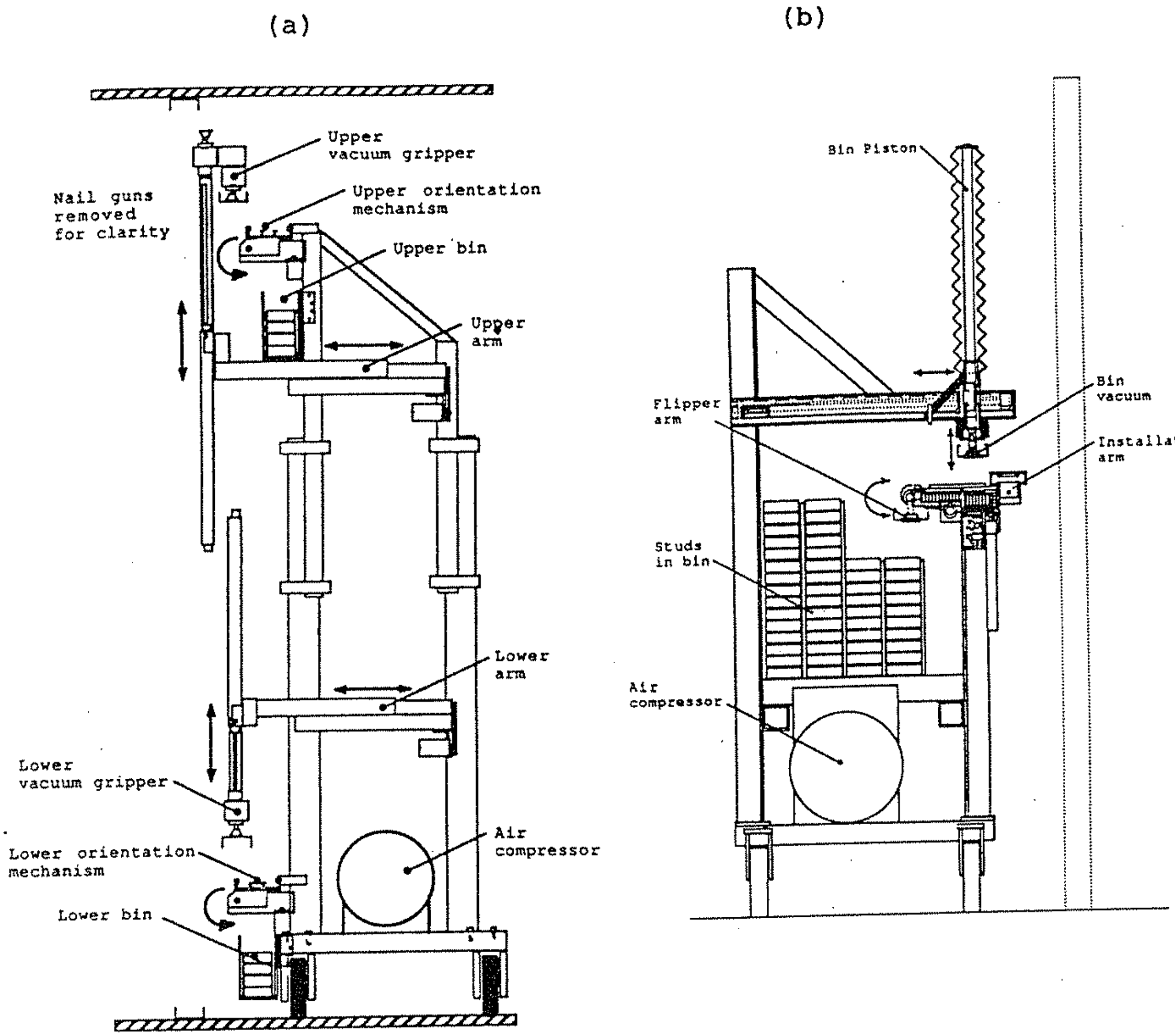
<u>Finishing</u> (Symbol: FIN)

FIN1 The Robotic Deriveter

Naval Surface Weapons Center, Silver Springs, Maryland, USA

The Robotic Deriveter is a mobile, flexible system designed to remove rivets systematically from Naval Aircraft, thus permitting inspection and repair of saltwater corroded airframe members. The system consists of a Smart Tool Head (to locate, inspect, and remove rivets), a Robotic Arm (to automatically position the toolhead), and a Computer Terminal (to control the process). This system represents one of the first major Navy developments in robotics. [39]

Figure 17 - Robotic system developed at Massachusetts Institute of Technology for installing steel tracks and studs for wall systems. The system consists of Trackbot, shown in (a), for installing the wall tracks in floor and ceiling; and Studbot, shown in (b), for installing the vertical wall studs between tracks. (Reprinted from [8].)



FIN2 Pipe Cutter

Water Research Centre, Great Britain

Britain's Water Research Centre and British manufacturers have developed a wide variety of remotely operated cutting tools for work inside pipes. [5]

FIN3 SSR-3 (Shimizu Site Robot-3)

Shimizu Construction Co., Ltd., Japan

This robot system has evolved through three generations of design, with each generation adding features and improvements. The first generation was developed in 1982. The general operation of the system is illustrated in the diagram of Figure 10 in the body of the report. It consists of a commercially available robot manipulator mounted on a mobile platform. It is designed to apply fireproof material (a slurry of rock wool and cement) to beams and girders of a building under construction. When accomplished by a human worker, the spraying operation is considered hazardous and uncomfortable because small particles of rock wool fill the surrounding area. The robotic machine maintains a sufficient separation between a human worker and the spraying operation to improve this condition. Compared to a tradesman who would otherwise perform this work, the robot's quality of workmanship is equivalent but its rate is faster. The robot is equipped with a position sensing system which adjusts the posture of the robot in relation to steel beams to be sprayed, thus permitting the robot to be in an optimal position to repeat the spray action. The third generation (SSR-3), developed in 1986, features off-line programming, on-board controller, and electric drive motors. [34]

FIN4 Painting Robot

Taisei Corp., Japan

Detailed information was not available for this report. [9]

FIN5 Automated Dry Docking System

Hitachi Engineering & Shipbuilding Co., Japan

This is a computer-controlled system designed to dock ships automatically in dry dock for maintenance work. During the docking maneuver, it uses suction cups attached to the ship's hull and sensors to ensure proper placement of the suction cups. After docking, the ship is automatically washed, blasted to remove scales and rust, and painted. This system is claimed to be three times faster than conventional methods and far less labor intensive. [9]

FIN6 Robotic Drilling and Riveting using Computer Vision

Lockheed-California Company, Burbank, California, USA

An experimental program using computer vision as a sensory feedback method for automated fastening of aircraft structures has been reported. The design includes computer controlled drilling and riveting equipment with a two-axis servo-controlled table for positioning of small, flat aircraft assemblies. Preliminary work using a five-axis robot for handling and positioning of small assemblies is also underway. Computer vision is expected to be of use in training, calibration, recognition, determination of position and orientation, fine positioning, verification and inspection. [21]

FIN7 An End Effector for Robotic Drilling

General Dynamics, Fort Worth Division, USA, and
University of Wisconsin, Madison, Wisconsin, USA

The robot drilling end effector was designed and built for the for the aerospace industry. Design features include: 1) automatic quick tool changing, 2) light and compact (38 lbs), 3) compliance mechanism to fit the counter of the wing, 4) drill and countersink in a single step. The design also incorporates five sensing devices. The device represents the results of extensive research into the operation of existing drilling tools and their inadequacies with regard to robotic implementation. [16]

FIN8 MTV-1 (Multi-purpose Travelling Vehicle)

Shimizu Construction Co., Ltd., Japan

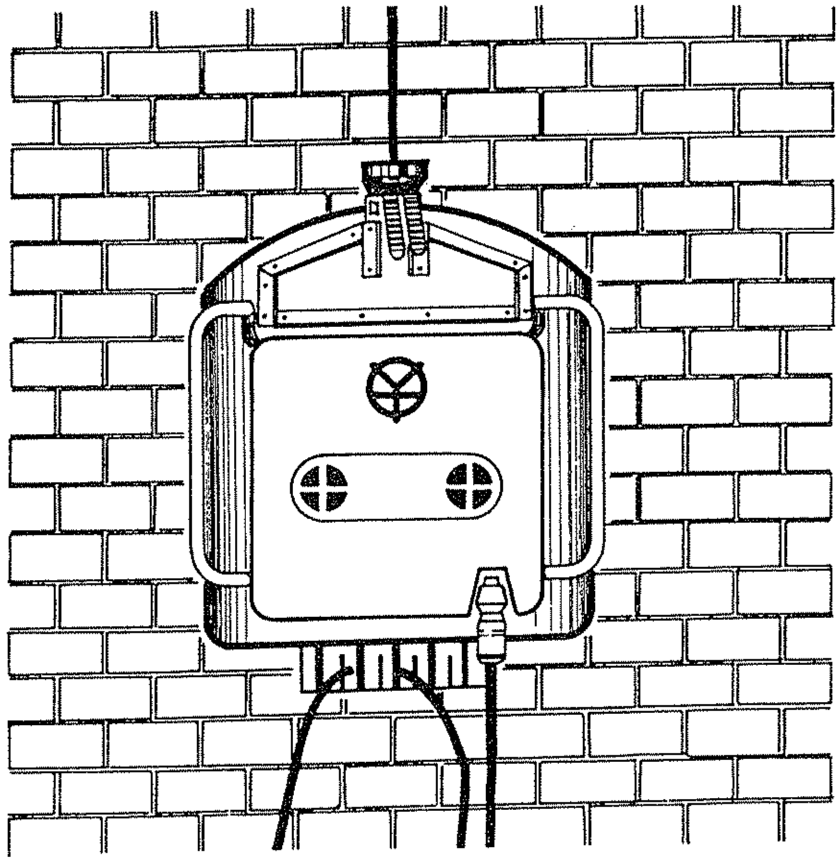
This machine is a battery operated vehicle to which work modules can be attached to perform various finishing operations. The system includes cleaning and grinding modules, which can be changed by means of two bolts and electric cable connections. The vehicle is capable of limited autonomous operation using its own on-board software. The machine can do many kinds of finishing work on concrete slab surfaces, travelling automatically and avoiding obstacles such as columns and walls. [31], [34]

FIN9 Exfoliated Wall Tile Detector

Takenaka Komuten Co., Japan

The inspection of exterior wall tiles for adhesion has conventionally been performed by human workers by tapping tiles lightly with a hammer to detect loose tiles. Loose tiles are thereby revealed by the sound during tapping. This teleoperated robotic machine, illustrated in Figure 18, is designed to detect weak bonds between tiles and external walls of buildings without the need for a human worker. It records the locations of these weak bonds on the wall. The benefits of using such a system are lower cost inspection, safety, rapid inspection, high reliability. Figure 19 illustrates how the device is operated. [1]

Figure 18 - Artist's sketch of exfoliated wall tile detector developed by Takenaka Komuten (FIN9).

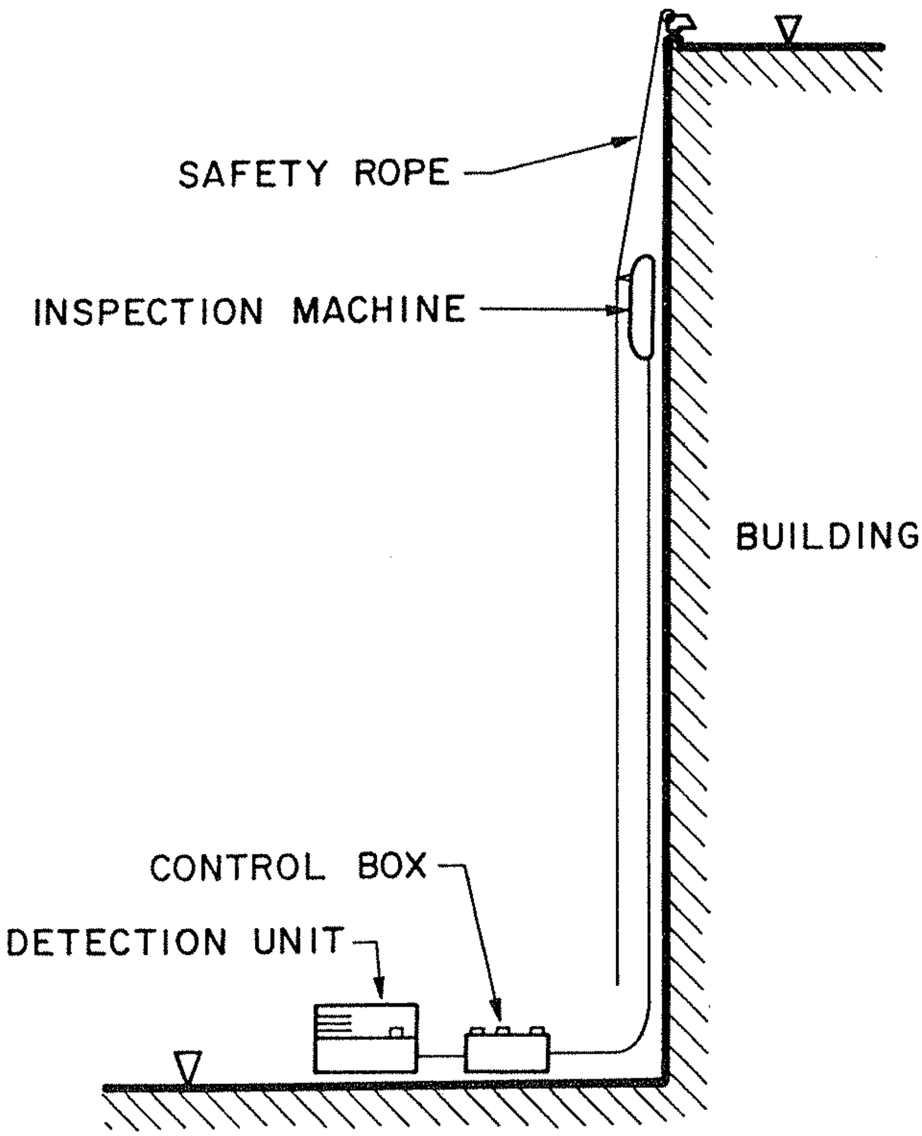


FIN10 Exfoliated Wall Tile Detector

Kajima Corp., Japan

This is another example of a wall tile detector. In fact this design precedes the wall tile detector by Takenaka Komuten Co. The detector includes four components: a travelling device set on the roof, a tapping device that travels along the wall, a controller, and a measuring device located on the ground. The general operation is similar to that depicted in Figure 19 for the wall tile detector by Takenaka Komuten Co. The measuring device consists of wave analyzer and a microcomputer, applying the principle of sound recognition. When the device detects the presence of loose tiles, the location is automatically recorded. Reliability is rated as high. [34]

Figure 19 - Diagram showing operation of wall tile inspection device developed by Takenaka Komuten (FIN9). (Redrawn from [34].)

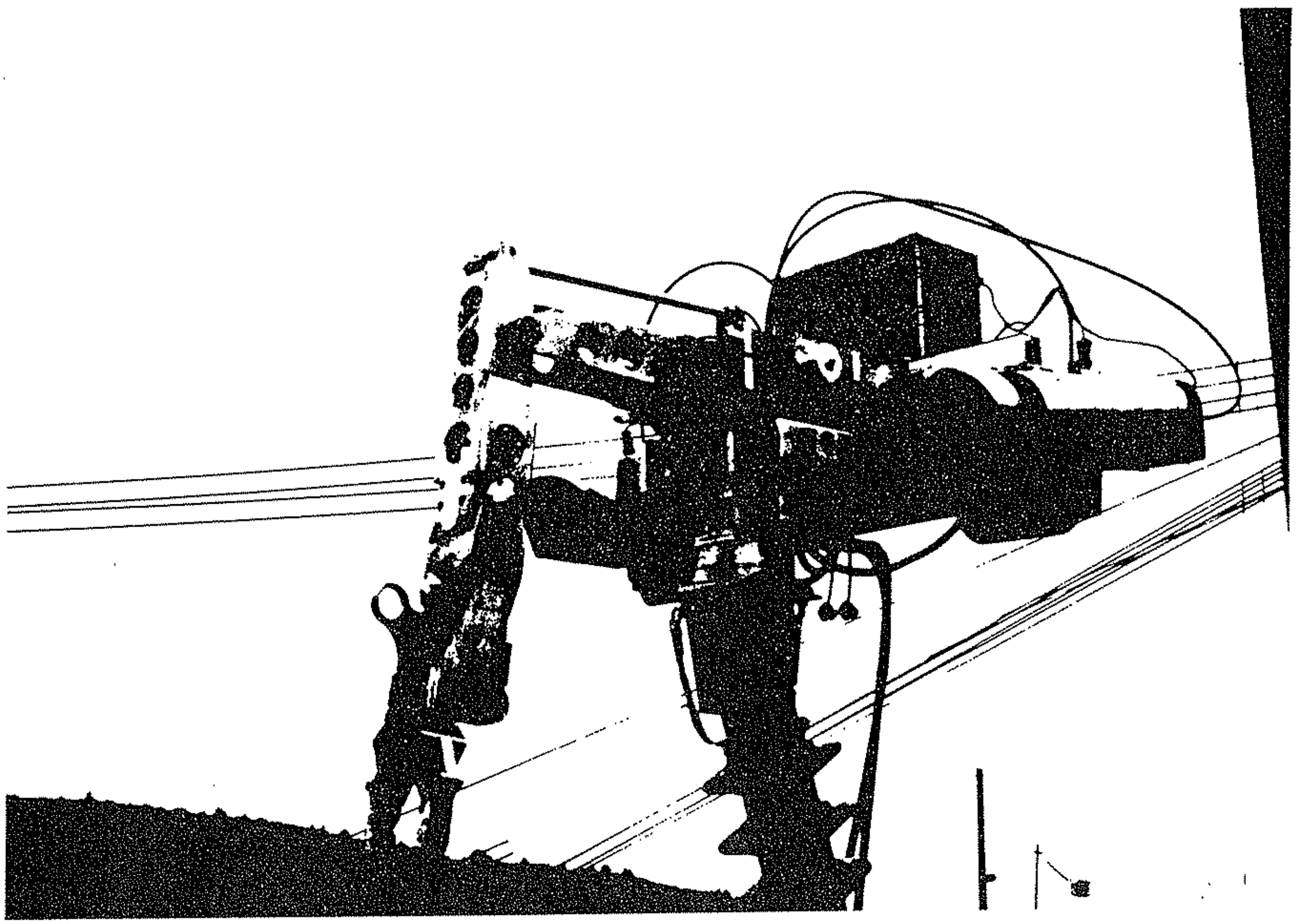


FIN11 TOMCAT Remote Manipulator for Transmission Line Repairs

Philadelphia Electric Company, Philadelphia, Pennsylvania,
Southwest Research Institute, San Antonio, Texas,
A. B. Chance Company, (location unknown), USA

This is a teleoperated manipulator that was developed with funding from the Electric Power Research Institute and the Empire State Electric Energy Research Corporation, with Philadelphia Electric Company, Southwest Research Institute, and A. B. Chance Company as the development contractors. The term TOMCAT stands for Teleoperator for Operations, Maintenance, and Construction using Advanced Technology. It has been used principally in the electric utility industry on an experimental basis for making repairs on transmission lines or to relieve "hot sticking" in power distribution equipment. As its name suggests, it also has potential applications in construction and is therefore included here as an example of a research activity in construction robotics. The device is operated remotely by a human located in a safe position. TV cameras mounted on the manipulator provide the operator with a view of the work area. This provides the sensory feedback needed to operate the device. TOMCAT is illustrated in Figure 20. [40]

Figure 20 - Teleoperator for Operations, Maintenance, and Construction using Advanced Technology (TOMCAT) used for transmission line repairs (FIN11).



FIN12 Exterior Wall Painting Robot

Shimizu Construction Co., Ltd.

This is a robotic system used for painting the exterior walls of residential high-rise buildings. Shimizu claims that it significantly increases safety of humans. [31]

<u>Demolition</u> (Symbol: DEM)

DEM1 Abrasive Water Jet Cutting Robot

Kajima Corp., Japan

The abrasive water jet method, which employs ultra high pressure water with an abrasive slurry, has been used to accomplish cutting of concrete during the construction of tunnels. It can also be utilized in demolition tasks and is included in the demolition category for this reason. The manipulator of an industrial robot was used to position and orient the water jet nozzle. This enables the device to cut concrete in any direction. The device is equipped with a "touch sensor" that maintains a constant distance between the nozzle and the surface of the material being cut. It is reported to provide very accurate cutting. A sketch of the device is presented in Figure 21 on the following page. [30], [34]

DEM2 MOOSE Robot

Pentek, Inc. Coraopolis, Pennsylvania, USA

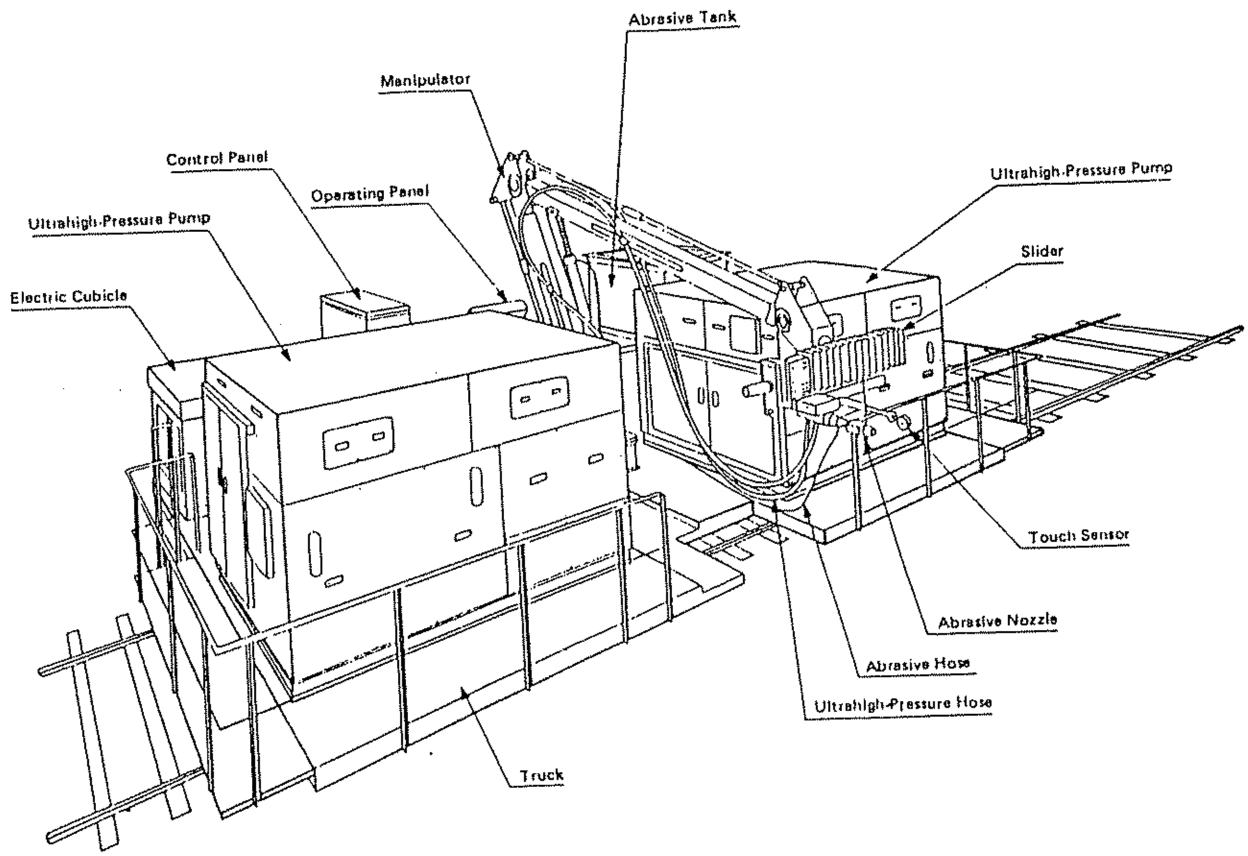
This is a mobile robot designed to perform certain operations, usually in nuclear facilities. The possible operations suggested by Pentek include concrete scabbing, paint or surface removal, reconnaissance, and plant security. The first unit was delivered to Three Mile Island Unit 2 in mid-1984 for floor decontamination in the containment building. Development funding was provided by the Electric Power Research Institute. Properly equipped with an automated hammer, MOOSE can deliver up to 1,200 blows per minute for breaking up a contaminated reactor building's concrete floors. The machine is illustrated in Figure 11 in the body of the report. [26], [27]

DEM3 Reactor Decommissioning Robot

Shimizu Construction Co., Ltd., Japan

This robot is currently under development and scheduled to be used in 1988. It will weigh approximately 14 tons. It is designed to cut up the reactor containment section of a nuclear power plant into removable volumes. [9]

Figure 21 - Abrasive water jet cutting robot used for cutting concrete during tunnel construction (DEM1). (Reprinted from [30].)



DEM4 Nuclear Decommissioning Robot

Taisei Corp., Japan

Detailed information was not available at time of report preparation. [9]

DEM5 Savannah River Laboratory Walking Robot

Savannah River Laboratory, Aiken, South Carolina, USA

This is a six-legged walking robot designed to lift up to 300 pounds and step as high as 30 in. Its manipulator can be extended 6 feet. The Savannah River Laboratory robot was designed specially to operate in a nuclear facility. [27]

DEM6 Remote Work Vehicle (RWV)

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

This is a teleoperated electrohydraulic system for remote work in the containment building basement of Three Mile Island nuclear power facility, Unit 2 (TMI-2), which was damaged in 1979. The RWV features a six-wheel platform to facilitate moving up and down ramps, four wheel-drive, and a tiltable, extensible boom which supports and positions boom-mounted tooling and a manipulator. Other features include on-board machine vision, omnidirectional locomotion, a tether for sustained power, and an off-board console located in a remote control room to permit operators to control vehicle functions. The RWV performs tasks such as washdown, sampling, material packaging and transport, surfacing, and demolition. [44]

DEM7 Remote Core Sampler (RCS)

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

The Remote Core Sampler represents the end effector tooling attached to the preceding RRV to cut, remove, and retrieve cylindrical concrete samples from the TMI-2 basement walls. [44]

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