FINAL REPORT

ROBOTICS IN CONSTRUCTION

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

The use of programmable robots for various kinds of repetitive and hazardous jobs in manufacturing industries is well established. However, their use for other tasks, as in construction, is still in a developmental stage, but is growing rapidly. Described in this report are current developments in robotics related to construction, both in this country and abroad. Also described are twenty types of highway construction activities where future robotic uses appear to be feasible. Basically, these are field inspection, component manufacturing, field construction, repair and maintenance, and general service support. Although most robots for use in construction still need considerable development, they appear to be technically possible, and could result in great efficiencies, saving of manpower, reduction in injuries, and minimization of the loss of life.

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INTRODUCTION

In the context of this report, it is believed necessary to define "robotics" and to provide some background on the subject.

Early man relied basically on his own muscles to perform work related to his survival. Simple tools as stones and sticks were sometimes utilized to assist this work, but the control and power were supplied directly by man. Gradually, through the centuries, machines of various kinds and complexities were developed to perform work either by their own direction and power or by minimal assistance of man. Machines operating by themselves essentially performed but one task, repeating it over and over again. Machines that were particularly controlled by man were generally somewhat more versatile.

Robots, derived from the Slavic word "robota," meaning work, differ from the preceding machines in that they not only function entirely on their own (once activated), but can be programmed to perform a variety of tasks. The latest generation of robots have even been described as being "intelligent," in that through their sensors and computer controls they can see, hear, feel, and even learn. Related to robots are devices called "telechirs," derived from the Greek language meaning "hands operating at a distance." Telechirs are thus defined as machines remotely controlled by human operators. Quite often, for general use, telechirs are also called robots.

Despite all the improvements and sophistication of robots likely in the future, man will be needed to perform most tasks. However, two general areas are seen where the use of robots is clearly preferred over the use of humans. The first is in jobs that are repetitive and boring for humans. Under these conditions, machines or robots usually perform more efficiently, effectively and economically than do humans. Assembly line industries, as those in the production of automobiles, appliances, and machinery, have found that industrial robots outperform humans in operations as spot welding, grinding, drilling, painting, and the like. The second areas of work where robots are preferred over humans is that involving danger to human life or limb. The use of robots or telechirs in these situations is justified on moral grounds, if not economic; although if illness, disability, and death costs are considered, economics is indeed an important factor. In industry, the use of robots or telechirs is growing where work has to be performed in a toxic or radioactive environment. Spray painting by robots is one of the most common applications in a hazardous environment.

In addition to these two major applications of robots, several others can also be cited. These are where robots can improve the quality of the work to be done, where they can increase productivity by increased speed of operation, where economy of manpower can be gained by their use, where around-the-clock operation is desirable or mandated, and where computer generated design data can be fed directly into working robots for automatic execution. This last application is as yet not a reality but with advances in computer aided design (CAD) and computer aided manufacturing (CAM), it is logical to project that design data in electronic form could be networked to construction robots without the need for intermediate drawings. Added to CAD and CAM would be a CAC (for computer aided construction) or RAC (robot aided construction).

DEVELOPMENT OF ROBOTS FOR CONSTRUCTION

Whereas robots have proven their worth in many industrial situations, their use in construction is just evolving. Some of the reasons for the slower evolution of robotics in construction as compared to industry are as follows:

1. Need for sophisticated designs to deal with variable and unstructured tasks encountered in construction, particularly in the field

2. Need for powerful robots to handle large objects and forces

3. Need for rugged machinery to operate in many kinds of weather conditions

4. Need for mobile robots to operate under field conditions, preferably without guides or tethers

5. Reluctance of manufacturers to invest capital in the development of construction robots in view of the technical difficulties and uncertainties of market place acceptance

Robots for construction can be classified by factors as "position", "program" and "use." In regard to "position", robots can be fixed in place (as are most industrial robots), moveable with a tether or guideway, and moveable without a tether. The fixed position robot would have primary application in a fabricating plant, as for welding, bolting, painting, or even placement of reinforcing steel. The moveable robots would have their best applications for field use, with the tetherless ones being preferred.

In regard to "program," robots can be remotely controlled by humans in real-time, preprogrammed to perform specified tasks (but capable of different programming operations), and heuristic in that they learn to perform the needed tasks somewhat as humans do through sensors and artificial intelligence in the form of complex computers. The current state of technology allows the first two types of "programs," but as yet allows heuristic operations only on a very limited basis.

As for "use," construction robots are needed to operate in factories (under controlled conditions), in the field (at ground level, aboveground and below ground under variable conditions), and in water (at the surface, below the surface and at the bottom; again under variable conditions). Since most construction operations are either in the field or in the water, the characteristics needed of these robots are quite demanding.

Despite the enumerated problems, some developmental work is going ahead with robotics and telechirs for construction. As early as 1978, Komatsu, Ltd. of Tokyo, Japan, developed a bulldozer that can operate underwater by remote control. More recently, Komatsu has developed and put to use an underwater robot that first levels seabed rubble and then compacts it to precise dimensions by means of a laser positioning system. It can clear over 2,000 square feet per day as compared to about 100 square feet per day achieved by divers. The unit has eight legs that enable it to traverse rough sea bottoms and it can move up to 83 feet per hour. Also recently developed in Japan is a self-propelled robot that sprays a mixture of rock wool and cement on steel building structures for fireproofing. Jointly developed by Shimizu Construction and Kobe Steel, this computer controlled robot can spray 20% faster than a skilled worker. Kokusai Denshin Denwa of Japan is developing a robot that can monitor seabed conditions along the path of submarine communication cables. It will soon be used to inspect and maintain submarine cables between Japan and China. Under development in Japan by the Hazama-Gumi Company is a shelf-driving "robot" for tunnel excavation. Controlled by an array of sensors it can tunnel along a planned route automatically. A prototype has been built and is being tested.

A stimulus for Japan's lead in developing construction robots is that country's Ministry of Construction, which has allocated $2 million for research on how robots can be used in design, construction, and maintenance. Numerous contractors and machinery manufacturers in Japan also are investing their resources in developing various robot type equipment applicable for construction. A partial list includes automated concrete distributors, automated shotcreting devices, stud-bolt-setting robots, and computerized and automated tunneling systems for monitoring, drilling, and mucking.

In the United States, the National Aeronautics and Space Administration (NASA) is investing heavily in research and development of robots and telechirs for miscellaneous work in outer space and for the construction of facilities in space and on the lunar surface. Already in use on the space shuttles are several telechirs. The principal one is a remotely controlled 48 foot long, articulated manipulator arm that has performed a wide variety of functions as deploying payloads, retrieving satellites, and even knocking blocks of ice off of the shuttle itself. Attached to the end of the arm is a light, a TV camera, and grips, all remotely controlled by an operator within the shuttle. Also successfully used by NASA are extraterrestrial based robots that have dug trenches in the soil of the moon and have surveyed the surface of Mars and transmitted the acquired data to earth.

Under study by NASA are even more sophisticated robots that could transport people, objects, and material from a space shuttle to a nearby space station. The space station itself could be largely assembled by free-flying robots. It is envisioned that other robots operating on the moon could collect raw lunar material and process it for application: either for the construction of lunar bases or for possible commercial use. The use of robotic front-end loaders (as an example) to scoop up soil at a lunar mine was seriously discussed at a recent meeting in Washington, D. C., sponsored by NASA to discuss the possible construction of a base on the moon. Many routine maintenance functions could also be done by robots instead of humans in the hostile environment of space.

Meanwhile, back on Earth,a number of organizations and industries in the United States are working on various kinds of robots for use in construction. The U. S. Army Construction Engineering Research Laboratory is investing approximately a half million dollars in the study of robots for rapid construction of wood frame structures. To date, it has found robots feasible in producing roof and floor trusses, along with wall panels. Perhaps the institution doing the most in this area is the Robotics Institute of Carnegie-Mellon University (CMU), which has a construction robotics laboratory directed by the Department of Civil Engineering, which is headed by Professor Dwight A Sangrey. The following is a list of projects they have in their laboratory for development.

1. A robot for boring and lining tunnels, which can also handle muck and debris. Sponsorship is by the Bechtel Group, Inc. of San Francisco.

2. A robot to clean out the radioactive sludge at the Three-Mile Island nuclear plant. A grant of three quarters of a million dollars has been provided by the owners of TMI of Pennsylvania.

3. A computer controlled, underground utility excavator that is sensitive to buried objects as power lines, tree roots, and the like. The project is in collaboration with the Dravo Corporation of Pittsburgh.

4. A mobile robot to locate underground pipelines.

5. A mobile robot to test concrete and locate reinforcing steel in a floor or bridge deck.

6. A robot to find and repair leaks in a pipeline.

7. A robot to shop-fabricate reinforcing bars.

8. A robot to lay bricks. The prototype machine can lay bricks of various sizes four times faster than a human bricklayer.

In June 1984, the Department of Civil Engineering at CMU held a workshop on robotics in construction that was attended by many interested people from around the world. Eleven trend-setting papers were presented on such subjects as the role of "expert systems" in construction robots, description of actual construction robots in use or under development, and the economics of such robots. The Proceedings of this important conference is cited in the Bibliography of this report. These Proceedings also contain hundreds of references on specialized topics relating to construction robots.

Because of the wide and growing interest in robotics in construction, CMU is holding a second conference on the subject in June 1985. Several hundred participants are expected from many parts of the world.

As an outgrowth of its 1984 Robotics in Construction conference, CMU is cooperating with the Technology Transfer Institute in Los Angeles in sponsoring a study tour in the spring of 1985 on robotics in construction and hazardous environments in Japan. The following is a list of the organizations on the itinerary, with their robotic speciality.

1. Kajima Corporation. Robots for setting stud bolts in nuclear power plants.

2. Takenaka Komuten Company. Robots for distributing concrete.

3. Shimizu Construction Company. Robots for spraying fireproofing insulation.

4. Ohbayashi-Gumi Company. Robots for handling large concrete panels.

5. Kumagai Gumi Company. Robotic operated excavation machinery.

6. Hazama Gumi Company. Boring capacity robots.

7. Komatsu Seisakusho Limited. Robots for underwater grading.

8. Hitachi Engineering and Shipbuilding Company. Robots for use in disposal of hazardous nuclear waste.

9. Mitsubishi Heavy Industry Company. Robots for use in disposal of hazardous nuclear waste.

10. Toshiba Corporation. Robots for use in disposal of hazardous nuclear waste.

At Stanford University, Professor Boyd Paulson of the Civil Engineering Department is conducting research on computer controlled guidance systems for such things as trucks, scrappers, cranes, and forklifts for application in construction. That such systems are possible is demonstrated by a new computer guided trencher and pipe laying machine (built by a Dutch firm) in use on a project near San Francisco. By virtue of this guidance system, the normal manpower crew of five has been reduced to two. Along similar lines, Spectra-Physics of Mountain View, California, has under development excavation and grading equipment automatically directed by beams of laser light.

Only to a limited degree is private industry in the United States doing R&D work on robotics for construction. For the present they see more profit from producing industrial robots than construction robots, and thus are cautious about investing heavily in an area of uncertain acceptance. Nonetheless some interesting examples of robots emanating from private industry can be cited.

Bendix Robotics of Southfield, Michigan, has built a small earth digging robot. Named MA510, it can lift only 22 pounds of payload, and thus is useful mainly for demonstration purposes. General Electric Automated Systems Division is investigating robots for loading and unloading large components, especially when housed in standard shape containers. Deere and Company of Moline, Illinois, is pursuing research on partially robotized construction equipment. For instance, an excavator could have an automatic "return to dig" program built into the machine so that at the press of a button or lever, the bucket would move back to a specified position. The Industrial Systems Group, located in Naperville, Illinois, has under development robots for welding, painting, and installing piping for ship construction. With modification, such robots could have application in building or bridge construction as well.

Miscellaneous types of robots that could have application in various aspects of the construction industry are also being worked on by others. One is a tractor that when driven once around the boundaries of a field to be plowed can then be programmed to plow the rest of the field in ever smaller patterns. Another is a heavy-duty log loader capable of lifting over 600 pounds. Its manipulators are partially computer controlled and partially human controlled. Still another is a self-propelled "fire fighter" tank that approaches a fire with a water hose and proceeds to automatically extinguish the flames. A similar kind of self-propelled mobile robot has been built to approach an unexploded bomb (as planted by terrorists) secure it, and then take it away for disposal. Yet another mobile robot is being developed to function as a roving security guard (as at a construction site). Equipped with cameras, lights, radios, and the like it senses any intruder and sends out an alarm for help. The Southwest Research Institute has under development a mobile robotic deriveter which identifies rivets on aircraft wings and removes them at less cost than by humans. The robot is of an emerging type employing a form of sight and artificial intelligence.

Although not exactly construction robots, numerous kinds of remotely operated vehicles (ROV's) are being developed and used by the U.S. Navy and the National Oceanic and Atmospheric Administration for underwater exploration. Other countries and private companies are also experimenting with such underwater vehicles. Popularized on television are those used by Jacques Cousteau and his associates. Remotely controlled manipulators attached to the outside of manned submersibles are extensively used to grab objects from the sea bottom for retrieval. Much of the technology used in undersea work of the kind described is directly applicable for the development of robots for underwater construction or repair.

An extensive two-year study on how robots and other automation technologies are likely to be used in construction by the mid-1990's has recently been initiated by the Battelle Laboratories in Columbus, Ohio. To be completed in 1987, the study is supported by 18 large construction and equipment firms in the United States, Japan, and Western Europe.

James S. Albus, in his article entitled "Robots in the Workplace" (listed in the Bibliography of this report), anticipates that during the 1990's robots will probably enter the construction trades, and that in the next century labor-intensive building techniques (using robot labor) may once again become practical.

POSSIBLE USES OF ROBOTS FOR HIGHWAY AND BRIDGE WORK

It is the writer's belief that robotics for use in highway related work will not arrive "fully grown." Rather it will evolve along two parallel paths. One path of development is that of programmable subroutines as installed on construction machinery (as bulldozers, cranes, graders, and the like). These computer controlled subroutines will take over a portion of the work now done by human operators. Unlike most present-day automatic controls, these new controls can be programmed to perform a range of tasks, sensing on their own what has to be done. Human operators will still be needed for those tasks requiring judgement.

Another path of development for construction robots is along the line of remote controlled or telechir equipment. For example, instead of sending a diver underwater to perform a construction task, a remotely controlled apparatus would be sent down and be operated and monitored by a human above water.

Only after much more sophisticated "intelligent" robots are developed will full robotization for construction be possible, because of the variable and unstructured conditions usually encountered in field operations. However, in some circumstances when field practices can be regularized or simplified, it is possible that robots could on their own do the required work, somewhat as is now done by industrial robots in manufacturing plants.

With these general conditions in mind, the writer in this section proposes a number of areas of possible uses of robots in connection with highway and bridge work. It is hoped that if application areas for robots can be pinpointed and justified, others in government or industry will be encouraged to pursue the development of such machines for general use.

An investigation of the various operations involved in highway and bridge work has disclosed many areas where robots or telechirs have potential application. In general, robotic applications for highway and bridge work fall under four categories; namely (1) field inspection, (2) manufacturing of components, (3) field construction, repair, and maintenance, and (4) general service support. Specific areas within these categories are listed below, along with comments concerning the nature of the robots that could operate in these areas.

Field Inspection

1. Culvert inspection. Because of the dangerous, dirty, and often difficult nature of inspecting the insides of culverts by humans, robots or telechirs are good candidates to do this kind of necessary work. The main characteristics for culvert inspection robots are the following:

a. Compact enough to fit into an average size culvert

b. Mobile and capable of negotiating curves and grades along flat or round culvert bottoms, possibly with running water and debris

c. Sensor equipped, with monitor control of movement, lights, and camera

d. Rugged and waterproof

Such a robot would be best used in long culverts where human access is difficult or dangerous. As the device moves along the inside of the culvert, video images would be transmitted to an operator outside the culvert, who would also have remote control of the robot and its sensors.

Somewhat less complex devices are already in use for the inspection of small diameter pipes or sewers. Generally, these devices are pulled along inside the line, and are equipped with a fixed wide-angle video camera that relays its images to an operator outside the line.

2. Bridge superstructure inspection. With approximately 600,000 highway bridges and tens of thousands of railway bridges in the country that require periodic inspection, the task of inspection is enormous. To make matters worse, human access for close inspection is difficult on most bridges. Under these circumstances, a good case can be made for the need for some sort of robot or telechir that could inspect superstructures.

It is envisioned that such a robot would be a remotely controlled device operated from the deck of a bridge and equipped with an articulated arm that could reach above or below the deck. A camera on the end of the arm would transmit its images to the operator on the deck. For this kind of telechir, the following are some of the characteristics needed.

a. Mobile, capable of locomotion along a bridge deck

b. Possessed of a long, articulated arm capable of reaching around corners

c. Sensor equipped with monitor control of arm, lights, and camera

d. Ruggedly built for outdoor use

Currently in use for the inspection of the undersides of bridges are mechanical "snoopers." Mounted on a truck, a U-shaped, articulated arm reaches around the deck to the underside of the structure. At the end of the arm is a bucket in which an inspector can stand to view the bridge. The telechir proposed would be a more versatile version of this snooper, and would be equipped with a remotely controlled camera instead of a bucket at the end of the arm. Such a telechir could be used not only to inspect the undersides of bridges, but also above-deck structures of through type bridges.

3. Underwater bridge inspection. The obvious hazards, difficulties, and expense of inspecting piers and foundations of bridges underwater greatly limit the amount of such inspection work currently done. The safety of the thousands of bridges could be at risk because of such limited inspection. Recent advances in mechanical submersibles along with video, remote control devices and sensors of all kinds strongly indicate that robots or telechirs could be developed to perform many types of underwater inspection. More frequent and extensive underwater inspection would thus be encouraged.

Listed below are some of the characteristics needed for an underwater bridge inspection robot.

a. Mobile, such that it can be easily brought to a site and lowered into the water

b. Compact, so that it can maneuver around bridge piers and foundations

c. Rugged, such that it can withstand high water pressure, corrosion, extreme temperatures, and bumping by solid objects

d. Positionally controllable, so it can be stabilized or moved slowly (even in fast flowing waters)

e. Equipped with lights and sensors capable of detecting failure or distress on any part of the bridge substructure under clear or turbid water conditions

Probably the most feasible device would be a telechir monitored and guided by a human operator above water (as on the bridge deck). Of particular difficulty is the development of a technique to "see through" turbid water. Possible solutions include fine-tuned sonic scanners or video cameras fitted with adaptable clear water bellows positioned between the lens and the structure.

Manufacturing

1. Shop welding. Robot welders are already in an advanced state of development and have been widely used in industry for several years. Most industrial robot welders are spot welders used to join relatively thin pieces of steel. Bridge construction mainly requires the welding of thick sections of steel, as by fillet or butt welding. Whereas automatic feed welders are in use, for such thick steel welding, they currently do not have the versatility of robot spot welders. However, development in that direction is ongoing. Ideally, the following characteristics are desirable for a heavy weld shop robot.

a. Moveable, such that for large components, the welder can be brought to the components

b. Programmable, so that it can automatically perform many different kinds of welds

c. Intelligent to a degree, in the event of some unforeseen situation

d. Ruggedly built

2. Shop fabrication of signs. Many thousands of highway signs have to be made yearly, either for new sites or for sign replacement at old sites. Although signs are of many different shapes, colors, wording, and graphics, there are a significant number of standards and generic similarities such that programmable robots could fabricate most signs. Centralized production of signs by transportation departments would offset the initial cost of acquiring sign-making robots. It is projected that a series of robots along a fabrication line would be needed. If it is assumed that large aluminum sheets are supplied, robots would first cut and drill the sheets to the required blank sizes, possibly by lasers. Self-adjusting machines would then feed the blanks into rollers that apply the background coating, which is in sheet form.

Programmable robots would take over again, cutting out the required lettering or graphics from sheet material (perhaps by lasers) and applying them at the desired locations. The following are some of the special requirements for these robots.

a. Capable of handling both small and large signs

b. Easily programmable, as directly from drawings

c. Capable of high speed operation

d. Sturdy

3. Fabrication of structural steel and reinforcing bars. Although machines of various kinds are already in use for the fabrication of steel components, a great deal of manhandling is still involved. To some extent robots could reduce these manpower needs, particularly for such tasks as cutting and bending steel bars and cutting and drilling steel plates. To a lesser degree, robots could be used to cut and drill rolled sections as well. Ideally, programming for these operations would be done directly from a drawing of the item to be fabricated. The robotic machines would then adjust themselves accordingly.

As an example, consider the fabrication of several hundred steel reinforcing bars, the majority of which are different from one another in regard to diameter, length, and bend configurations. A programmer would classify these patterns into similar groupings and program the machines to perform the necessary operations of cutting and bending each bar in sequence. Thus, long, straight lengths of stock steel would enter one end and exit the other as the required several hundred bars, all individually finished and labeled without human intervention.

The demands and special features of these programmable machines are many, and some of the major ones are as follows:

a. Capable of handling a wide range of component sizes

b. Of sufficient power and ruggedness to cut, drill, and bend steel on a quantity basis

c. Easily programmable

d. Equipped with safety devices in the event of malfunction

4. Placing of reinforcing bars in forms of precast members. A programmable machine to place reinforcing steel is suggested as a possibility to reduce hand labor in precasting plants that do a high volume of work. Involved would be the need for a robot to select the proper bar, transport it to its correct position in the form, and then firmly secure it. An alternative procedure would be to have robots prefabricate large sections of the reinforcing as a cage or mat outside the form, and then place and secure the prefabricated unit in the form. Either process would require robots with at least two long arms capable of coordinated large-angle articulations. The technology of multiarmed robots is still evolving, so machines of this nature will not be practical for some years. It can be noted, however, that research in this area is already under way in Japan. In a related operation, the Japanese are also researching the use of robots for assembling and handling large concrete panels and other castings. A prototype robot for this purpose has already been built.

The following are some of the main characteristics needed for rebar-placing robots.

a. Capable of handling both short and long bars of various bent shapes

b. Equipped with a device to secure the bars to one another and to the form

c. Easily programmable

It is possible that although such a robot could be built, it's complexity would make it too expensive for general use. A less expensive machine would be a telechir, which would be largely controlled by a human operator.

Field Construction, Repair, and Maintenance

1. Striping roadways. Millions of miles of roadways have to be striped yearly, an activity representing many millions of dollars. Currently, various kinds of specially equipped vehicles are used to apply the needed paint or plastic stripes. However, these vehicles all require human operators to guide them and control the application of the paint or plastic. Since the geometry of the roadway is a known quantity and the locations of the stripes can be predetermined, it is conceptually possible for a mobile robot to do the job. The development of such a robot is one of engineering in which reliability, safety, and ease of maintenance are important. It also seems prudent that the operation and position of these robot stripers be monitored by a human, either onboard or at a remote location. Various kinds of guidance systems, such as

optical sensors controlled by the edges of the pavement, or sensors detecting pre-placed markers in the roadway, appear possible. Sensors would also be needed to detect obstacles in the path of the robot, which might be debris or other vehicles.

Assuming these parameters, the following are some of the main features needed for robot stripers.

a. Compact and self-propelled

b. Programmable for various types of lines, as single, double, solid, broken, straight, or curved.

c. Capable of guiding itself and laying down stripes as required

d. Equipped with adequate traffic safety and fail-safe features

e. Ruggedly built and easily serviced

2. Culvert repair. The repair of culverts is a dirty and dangerous job. Obviously, anything a robot or telechir could do would be to the good. Although it is anticipated that some type of repair work would still have to be done by humans, many standard repair procedures could be done by robots. Two types of culvert work are candidates for robots; namely, cleaning and minor leak or corrosion repair. Long culverts of relatively small size are particularly well suited for robotics work in contrast to human efforts.

Considering the possible irregularities of culvert bottoms (as caused by holes or debris), some sort of walking type locomotion system would function better than a wheeled system. For maximum versatility, the robot would have two separate, basic components. One would consist of the power, computer, and locomotion system, and the other of the articulated arm system. Depending upon the nature of the job to be performed, different type arm components could be attached to the general locomotion component. For example, to repair a spalled concrete culvert, an arm package would be specifically constructed to clean and seal the damaged areas. Spray type cleaning and sealing would be the simplest method for these operations.

Remote control of the arms would probably be necessary to some degree, with certain standard subroutines programmed into the machine. Video monitoring would allow such remote control as well as ensure that the work was done properly. For large repair jobs, and extra carrier robot may be needed to transport material to and from the repair site in the culvert where supply by flexible pipeline is not possible. The design of such a carrier robot would be relatively simple as it would not need moveable arms.

In summary, the following are the main features needed for culvert repair robots.

a. Capable of locomoting through culverts with irregular bottoms

b. Able to perform general cleaning and repair functions, either automatically or by remote control, on concrete and metal culverts

c. Ruggedly built and waterproof

d. Equipped with lights and video camera

3. Underwater repair. One of the most difficult repair jobs is that done underwater. Bridge piers damaged by water, ice, or impact, and foundations weakened by scour are some of the more common problems requiring attention. Because of all the difficulties in working underwater, such repairs are generally major undertakings requiring the extensive use of human divers. Robots or telechirs could play a role in performing much of this difficult underwater work; thus, reducing the hazards to the divers. Other advantages of robots over divers are that they can work for much longer time underwater, they can be designed to be much more powerful than humans, and, in the long run, they could reduce the cost of repair.

To make underwater repair robots as adaptable as possible to meet a variety of conditions, a tethered, remotely controlled machine may be the best approach to its design. Locomotion would be along temporary guide rails positioned near the pier or foundation. Working from these rails (which could be either vertical or horizontal), the robot's arms could be directed to perform whatever operation is required. For complex operations, several coordinated robots may be needed. Sensing could be by a combination of video and sonar.

Obviously, the method of repair used must be matched with the capabilities of the robot, although some human diver assistance may at times be required. Such standard operations as attaching repair collars and grouting could generally be done by robots.

Assuming underwater repair robots to be of the type described, the following summarize the primary characteristics needed.

a. Able to locomote along guide rails in the water

b. Equipped with arms and grips that can perform a variety of tasks

c. Remotely controllable

d. Programmable by subroutines

e. Equipped with underwater sensors

f. Ruggedly built and waterproof

4. Cutting grass. In one sense, the mowing of grass is a simple operation in that only one basic task is performed; that of cutting along a surface with a mechanical blade of some sort. In another sense, it is a very complex operation as the mower has to be carefully maneuvered along different types of topography, often studded with obstacles as posts, trees, bushes, and debris. Because of the latter aspect, a robot designed to cut grass along highway rights-of-way must be guided by some form of artificial intelligence. Programmed into its sensors and computer would be a need to recognize objects as posts, trees, bushes, rocks, roadway, fences, cut grass, uncut grass, etc. Controls linked to the computer would direct the mower to avoid certain areas and cut only where needed. Limits on how far to mow before turning around would also have to be programmed into the robot.

Of great help would be landscaping so laid out that difficulties in mowing could be minimized without sacrifice in esthetics or function.

The required sophistication of a robot mower for general use is such that its development is probably a long way off. Nevertheless, the following is a list of the major features needed for such a machine.

a. Self-propelled, with adjustable grass cutting blades

b. Self-directing to mow only where required

c. Equipped with shutdown safety features in the event of an unusual situation

d. Ruggedly built and easily maintainable

5. Grading and excavating. It is conceivable that certain types of earth moving could be accomplished by robot machines. The type most suitable would be that requiring grading or excavating over a relatively limited area with definable topographical and geological features.

Consequently, a digitized map of the area prior to earth moving would be programmed into the computer of the robot.Then a second digitized map of the area in its intended altered configuration would be programmed. Following this, a series of basic machine movement commands would be introduced so that grading or excavating would proceed from map one to map two. Several laser control stations (set up outside the work area) would help guide the robot by means of a laser intercept antenna mounted on the earth mover. The needed software and guidance controls are not simple, but are technically possible. Various fail-safe features must also be considered, such as for an unexpected encounter with a large boulder or cave-in of a trench. In such situations, a manual override of the controls may be necessary.

The characteristics to follow are those basic to a robotic earth mover.

a. Self-propelled and powerful enough to move large quantities of soil and rock

b. Capable of being programmed to execute a sequence of earth moving operations

c. Equipped with automatic shutdown features in the event of an unexpected situation

d. Ruggedly built for all weather conditions

6. Painting and cleaning bridges. In industry, the use of robots for painting is commonplace. However, there is a great difference in the repetitive painting of new small objects done in industry and the individualized, large-scale cleaning and painting of a bridge. Because of this difference, little of the methodology employed in industry is applicable to field painting of bridges.

Since almost no two bridges have the same configuration, it is desirable for a bridge-painting robot or telechir to be as versatile as possible. It is assumed that the cleaning of the bridge prior to painting could be done by the same basic machine as for painting, modified only in its ability to handle a surface spray cleaning or blasting agent instead of spray paint.

Of the many possible ways to manipulate the robot cleaner-painter, the most adaptable is thought to be at the end of a long, articulated telescoping boom, with the boom mounted on a vehicle which can ride along the deck. The boom should be such that it can be either raised up (to paint overhead structures) or looped around and under a bridge (to paint the underside of a structure). Both devices are already widely used in bridge inspection and repair work. The difference is that instead of a human in a bucket at the end of the boom, there would be a mechanical robot or telechir. For the cleaner-robot, a video camera monitored by a human operator is all that is needed as a sensor. The type of sensor needed for the painter-robot could be a pulsating beam of light that by reflection would register the distance to the surface, the nature of the surface (smooth metal or rough concrete) and whether or not the surface was wet with paint. Although a video camera could be used in addition, its operation would be only as a secondary control in that its lense would have to be automatically covered during actual spray painting to avoid coating.

Exactly how much the robot can be preprogrammed and how how much it would have to be remotely controlled depends on the degree of sophistication of the robot and computer control software. Theoretically, it could all be preprogrammed as the bridge configuration is fixed and known in advance. Practically, however, some combination would probably be less complex.

In summary, the following represent the basic features needed in a bridge cleaner-painter robot.

a. Mountable on an articulated telescopic boom

b. Capable of handling hoses and nozzles of various kinds

c. Capable of being programmed or operated remotely

d. Equipped with optical or other sensors

e. Easily maintainable

7. Patching holes in pavements. Potholes are a pervasive problem of seemingly endless magnitude consuming a great deal of time and energy on the part of maintenance personnel. It is estimated that over 50 million potholes have to be filled annually in the United States at a cost of approximately $250 million. In Virginia alone, over 2 million potholes have to be repaired every year. In addition, the hazards to personnel working under traffic conditions are not to be overlooked. Robots could perform the repair work faster and with less danger to personnel.

Although the same basic programmable machine could be used for repairing bituminous and concrete pavements, some modifications would have to be made for each material. It is envisioned that the robot is a wheeled vehicle that can be brought to a hole requiring repair. A human operator would set the dimensions for repair (width, length, depth, rectangular or circular) into the computer controls of the machine. Depending upon the pavement material, an appropriate cutting or digging tool excises the hole to its programmed size. A vacuum system removes all debris from the hole during this process and ejects it into a closed bin onboard the vehicle. After the hole is cut and cleaned, the necessary coating and filling materials are automatically applied and tamped or leveled even with the adjacent pavement. In the case of concrete pavements, it is assumed that a rapid setting binder (perhaps other than portland cement) is used so that traffic can be permitted on the patch within minutes of placing. A heater could be employed either for softening of bituminous material or accelerating the hardening of the concrete patch.

It is desirable that a human operator monitor the work of the robot to ensure that everything is done properly. After the hole is repaired, the operator would then move the robot to another one.

The main requirements for a pothole robot are as follows:

a. Mobile and relatively compact

b. Equipped with automated concrete or bituminous pavement excising tools

c. Capable of vacuum cleaning a hole clear of debris

d. Able to handle various kinds of liquid or plastic material for coating and filling holes

e. Able to compact and level a patch

f. Programmable to the extent of excising a hole to a given configuration and filling it with rapid setting material

g. Sturdily built for outdoor use

It is to be noted that several mechanized bituminous pothole patching machines are already available which incorporate some of the features needed in a programmable robot of the type described. Currently, the one most mechanized is the Gabriel Perma-Patch machine, developed by the Perma-Patch Company.

8. Fastening structural members. There are fewer more hazardous jobs in construction than "high steel" work. As presently conducted, steel workers have to climb out on exposed structural steel members, relying primarily on balance to keep from falling, often hundreds of feet to the ground. To a somewhat lesser extent, field connecting precast concrete members is similarly hazardous. As one of the functions of robots is to replace humans in dangerous jobs, the development of robots to fasten structural members in the field (such as

by pinning, bolting, or welding) is a proper objective. Unfortunately, the job of making field connections is multifaceted, and thus would require a rather complex robot. The robot must first guide the member into position to within a fraction of an inch of its intended location, then permanently fasten it with bolts or welds. Generally, each of these operations is unique to each site and situation.

Until a "super-smart" robot can be developed, reliance has to be placed on control and manipulation by a human operator using a two-armed telechir. One arm would grasp the member and lead it to its proper position and the other would then do the fastening. The construction of the telechir can be greatly simplified if the connection is so designed as to easily interface with the machine. Usually, this means that a connection should be designed to be made from one side only. For welding, a full penetration weld done from one side is suggested. For bolting, a special bolt with a tapered lead inserted into a premounted threaded nut is a possibility.

Also to be developed is the best way to position the robot such that it can secure a connection, yet be easily repositioned for other connections. Probably the most workable method is to suspend the robot at the end of an articulated boom for purposes of moving it to various locations. At each connection location, for stability the robot would clamp itself to a fixed member from which it then would function. In all operations of moving and fastening, a video system on the robot could allow a human operator to direct the work by remote control.

In brief, the following are the essential characteristics needed for a robot to fasten structural members.

a. Compact and portable such that it can be moved from connection to connection easily

b. Equipped with at least two arms, one for grasping the structural member and one for making the connection

c. Equipped with video and remote control systems

d. Provided with an adaptable, remotely controlled clamp for fastening of the robot to a fixed member

e. Ruggedly built for outdoor use

For a related field operation, the Japanese have built a huge prototype robotized arm that distributes and places wet concrete on building floors under construction using the method of pumped concrete. Its economy, however, is yet to be proved.

9. Changing lamps on lightpoles. Although some of the high mast luminaires used for highway lighting have a built-in lowering mechanism for ease of changing lamps, most are of the fixed variety. At present a human has to be sent up to these fixed luminaires at some physical peril. Since the specifics of replacing lamps in a luminaire are essentially the same for each type of luminaire, a robot could be built to perform such standardized operations.

Needed would be a mobile truck with an articulated boom fitted with a robot or a telechir. Such trucks and booms are already in common use. Three basic types of robots are possible for this purpose. The first type would be a fully preprogrammed machine matched exactly with a specific luminaire that would open the refractor cover, remove the old lamp, install a new lamp, and then close the cover. Cleaning of the cover could be an optional feature, although a specialized cleaning robot may be preferable, as described later in this report. A second type of robot would be more adaptable, but would require some remote control by a human operator. Monitored by a video system, an operator would direct the primary movements of the arms and grips of the telechir. A programmed subroutine would perform a standard procedure as screwing or unscrewing automatically on command. A third type of robot would be an advanced machine with built-in intelligence. Unlike the first type designed to interface with one specific type of luminaire, this "smart" robot would identify the critical components of any luminaire and proceed to mechanically change the lamp, using its sensors, arms and "soft-touch" grips, much as a human would do. Obviously, such intelligent robots are of a future generation. To make any of the robot designs less complex, a different connection configuration might be helpful.

Regardless of which of the three types of lamp-changing robots is considered, the following are the essential features needed.

a. Capable of being positioned adjacent to high luminaires (as with a telescopic boom mounted on a truck)

b. Able to perform the various operations necessary to replace a lamp in a luminaire

c. Built for outdoor use

10. Washing signs and luminaires. Washing the millions of signs and luminairies on the nation's highway system is such an extensive operation that it is seldom done on any regular basis. Robots would

permit this work to be done rapidly, efficiently, and at less cost than having it done manually. A robot or telechir designed for washing does not have to be very complex as close tolerances of arm movements are not needed. A possible working head would consist of a rotating brush fed with detergent water. At the center would be a vacuum drain to collect the wastewater so as to minimize environmental damage due to runoff. Guidance control of the scrubber would be preset in a programmable computer depending upon the geometry of the object to be cleaned. It would be necessary for a human operator only to position the scrubber initially at some determined point on the object and then activate the robot. It is assumed that the robot would be mounted at the end of a moveable boom mounted on a truck.

In summary, a brief description of the main characteristics needed for a sign-and-luminaire-cleaning robot is as follows:

a. Relatively light and easily moved

b. Capable of scrubbing flat and curved surfaces rapidly

c. Equipped with a vacuum system to avoid environmental pollution of cleaning agent

d. Programmable for automatically directing the cleaner over any specified geometry

e. Built for outdoor use and easy maintenance

General Service Support

1. Loading and unloading operations. Loading and unloading material and objects transported by trucks are operations performed many thousands of times a day in repairing and constructing pavements and highway structures. Human operated lifting machines and vehicles (such as forklifts) are commonly used, but in some modern warehouses automatically guided machines "fetch and carry" objects from one place to another. Generally, in such a warehouse, every different object is stored in a separate bin in a known location. When a particular object is required, a mechanical carrier is automatically dispatched to the proper bin and brings the object to the required location (as to a shipping area). In like manner, this type of automation or robotization could be developed for loading or unloading operations in an outdoor storage area where there might be a large volume of work.

For example, a storage area might contain quantities of precast concrete components of different sizes and shapes that are used daily.

A robot, guided electronically by an underground network of signal wires, could be dispatched to get the specific precast component needed, bring it to a loading dock and perhaps even load it on a truck. In reverse, when the storage area supply runs low, the robot could unload the truck carrying the various components and automatically deliver them to their proper storage locations.

A robotic crane for moving material from a truck or the ground to some position elsewhere (as on a bridge under construction) is also within the realm of possibility. Coordinates of the destination of the object and its size would be fed into a computer that would store in its memory and display on a screen the current as-built outline of the structure. The robotic crane would then move the object around the structure so as to place it correctly and without hitting anything en route. A stand-by human monitor is advisable to override the automated system in the event of some unforeseen situation.

The following items represent a digest of what is need for robots to load and unload objects or materials.

a. Able to move along guided paths

b. Strong enough to grasp and lift heavy weights

c. Programmable to move in various ways

d. Built for outdoor and heavy duty use

2. Servicing vehicles. A great many vehicles of many types are used regularly in construction, and all of them require periodic maintenance and repair. Over the years, numerous special tools and machines have been devised to perform these servicing functions, almost always with the direct aid of a skilled technician. Because some types of servicing are rather standard as well as frequent (for example, the changing of tires), robots could be built to do these repetitive jobs. In some automobile assembly plants, robots already are at work installing wheels on new cars.

Other frequent service functions on vehicles include adding gasoline and water, changing oil, replacing batteries, checking tire pressure, cleaning windshields, and washing vehicles. Although automatic car washes are already in extensive use, automatic washing of other types of vehicles as trucks, bulldozers, and the like is still done manually.

It is believed that robotic engineers could design robots to do any of the tasks mentioned. However, the cost of designing and building these machines has to be balanced against the economic benefit of replacing human workers. Since robotic servicing would likely be faster than manual servicing, robots would be economically feasible only in high volume operations, such as in large central garages where many hundreds of vehicles are serviced daily.

Since there are many possible kinds of robots for servicing vehicles, only one will be singled out; namely, that of a wheel changer. It should have the following basic characteristics.

a. Programmable to adapt a large variety of wheel sizes and types

b. Capable of undoing and redoing wheel lug nuts rapidly

c. Capable of holding and handling a range of tire sizes

d. Ruggedly constructed

It can be assumed that after the robot has removed the wheel on which a defective tire is mounted, another machine or robot removes the tire from the wheel and replaces it with either the repaired tire or a new one. The wheel is then returned to the wheel changer for reinstallation on the vehicle.

3. Security patrolling. On construction job sites there is a high rate of theft and vandalism, which adds to the cost of a project and may cause time delays as well. Various measures are often taken to reduce such problems, most of which are rather expensive. As the development of robots continues, it will soon be possible to assign one or more mobile robots to patrol a job site, in lieu of other, more expensive solutions.

Visualized as one possibility is a mobile roving robot equipped with a light enchanced video camera, sound detector, heat sensor, movement detector, and pattern recognizer, along with an alarm system. Upon recognizing an unauthorized intruder, the sentry would sound a synthesized voice warning as well as send information concerning the intruder back to security personnel. The route of the robot could be changed daily to eliminate the possibility of an intruder knowing in advance where the roving security robot may be at any given time. In some instances, the robot might even spray some form of chemical on the intruder either for immediate pacification or later identification.

Many variations on the types of security patrolling robots are possible, depending on their particular applications. Some may need to operate on wheels, some on tread belts and others may require walking legs. The last type is believed to be the most adaptable for different terrain conditions. Some robots may need only to transmit a video or audio signal to a security guard, while others may actually apprehend an intruder (as by gassing or electrically stunning).

Aside from possible economics of using robots for patrolling, no human security guard would be at risk from an intruder armed with a lethal weapon.

Because of the wide range of security robot types possible, the summary of requirements for these robots is rather general.

a. Capable of self-locomotion over uneven terrain

b. Equipped with sensors of various kinds capable of detecting an intruder

c. Programmable in regard to routing

d. Constructed for outdoor use

e. Capable of pacifying or apprehending an intruder, as an optional feature

CONCLUSIONS

Discussed in somewhat specific terms is a wide range of types of highway and bridge related work where robots or telechirs could prove useful and valuable. As robotic development grows, many other applications probably will arise. Some of the robots described need only minimal development to become operational, while others need extensive research and development. Yet all are believed to be technically possible.

The unresolved question is how cost-effective these future robots will be. In situations where human lives could be saved, the question of morality also enters. If even an expensive robot could save one life, is it worth it? However, a number of the robots and telechirs described are believed to be economically feasible and would perform their tasks faster and more precisely under hazardous or repetitious conditions than can humans. Confirmation that this may be so is given by private industry, which here and there is developing robots for some kinds of construction work. Virtually all large engineering schools have an ongoing research program in robotics, and at least two are specializing in construction robotic research and development. Others are expected to follow.

To be sure, the widespread use of robots for highway and bridge work will not arrive tomorrow, but it is highly likely to be here by the end of the century. For engineers and other designers oriented to the future, long-range planners and forward-looking managers, the use of robotics in certain areas of construction should be taken seriously. It is hoped that this anticipating study will help to keep them abreast of what is happening and what is possible in the near future.

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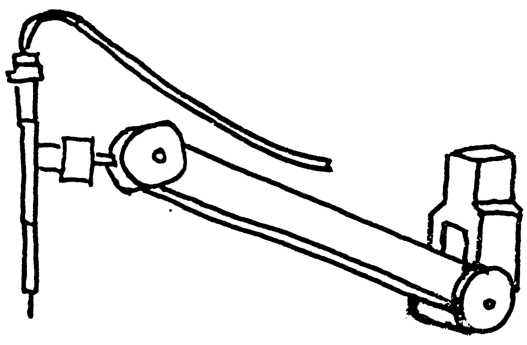
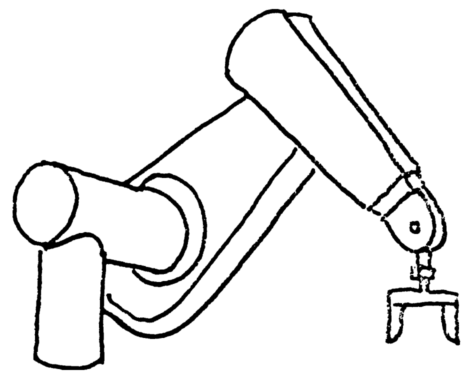
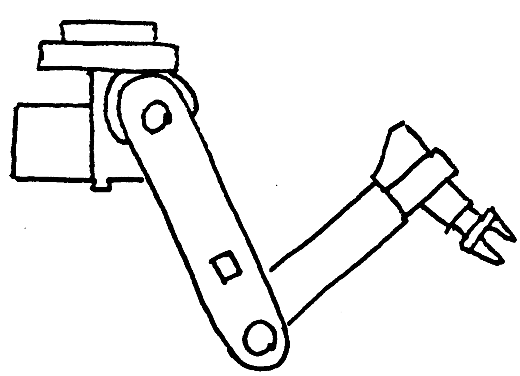
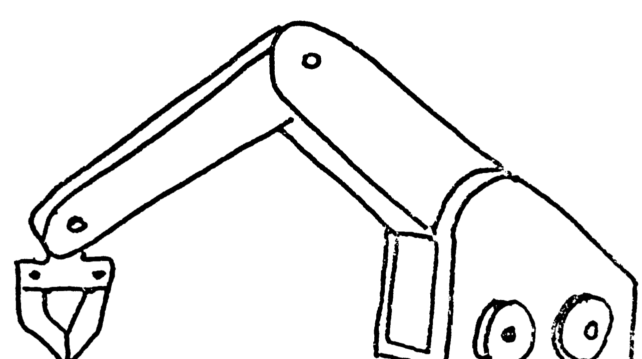
APPENDIX



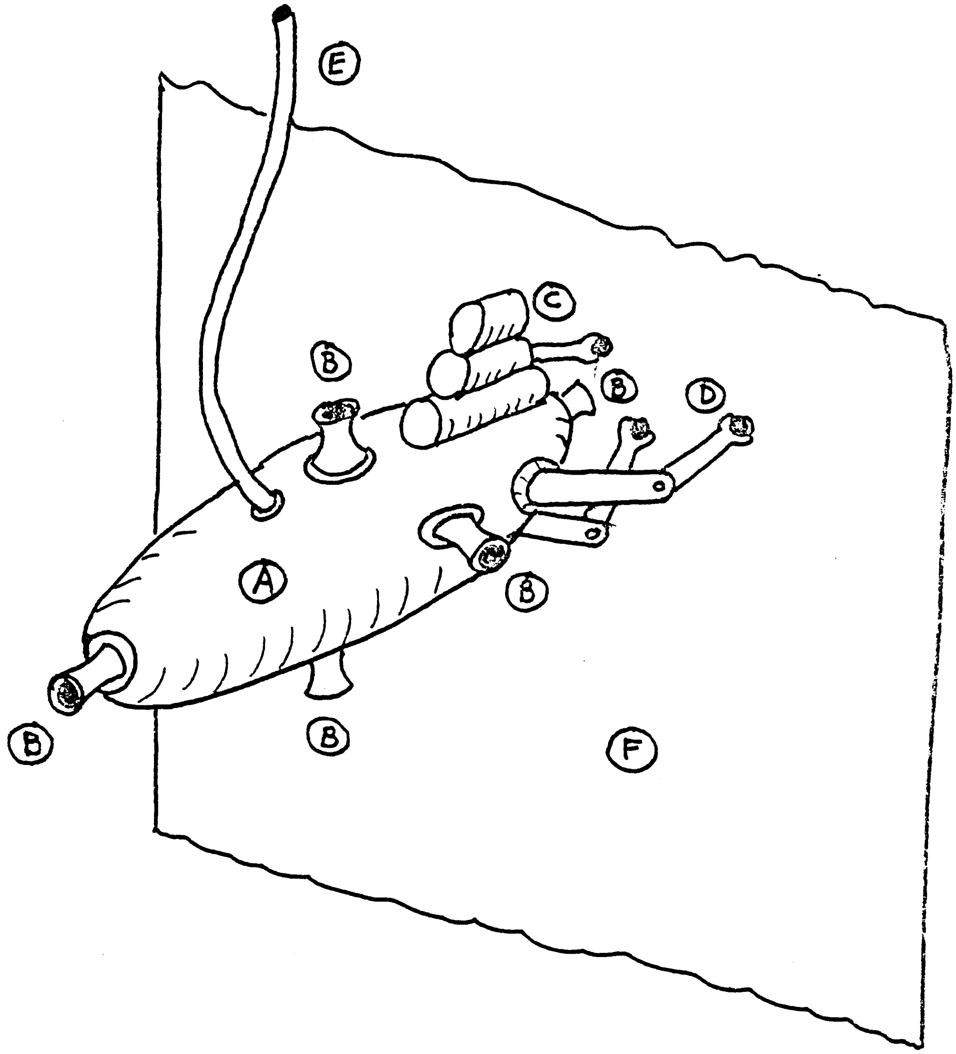


Concept Sketches
for some
Highway Related
Robots





Underwater Bridge Inspection Robot



Ⓐ Bouyant neutral vessel

Ⓑ Computer controlled thrusters

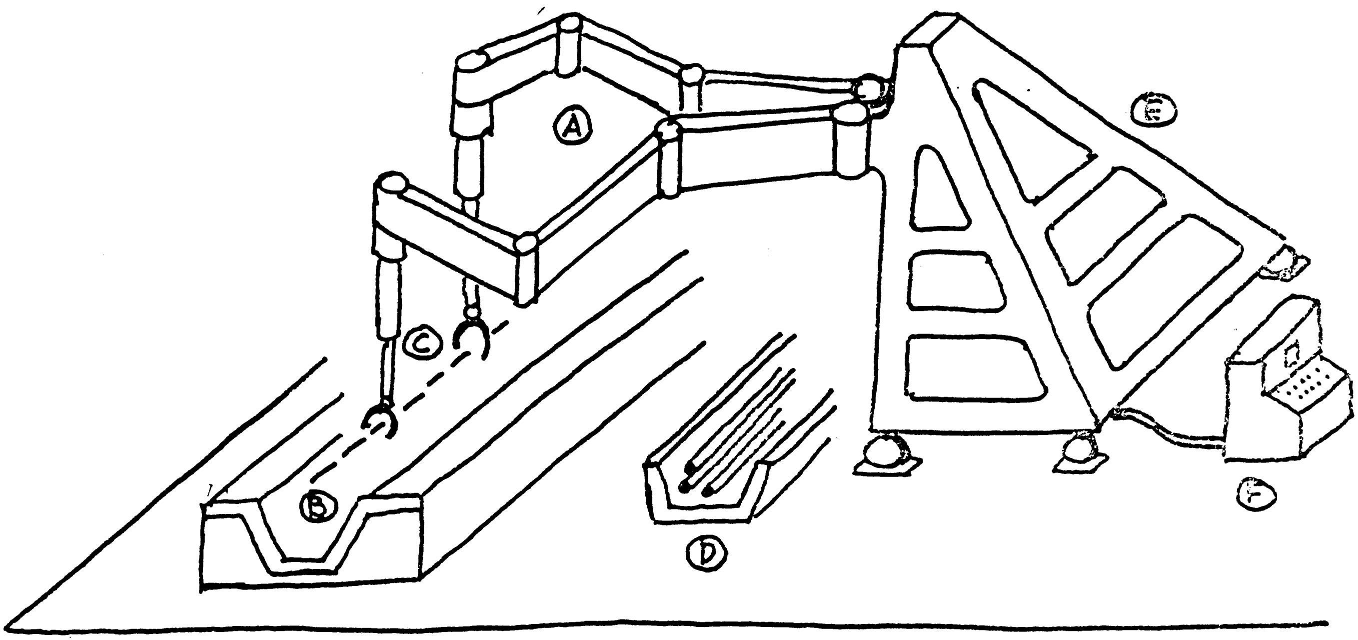
Ⓒ Image intensified video camera, sonar scanner and light

Ⓓ Triad of remotely controlled feeler-stabilizers

Ⓔ Tether, with power and communication cables

Ⓕ Underwater portion of bridge

Reinforcing Bar Placing Robot



Ⓐ Pair of computer controlled robotic arms

Ⓑ Reinforcing bar being placed in form

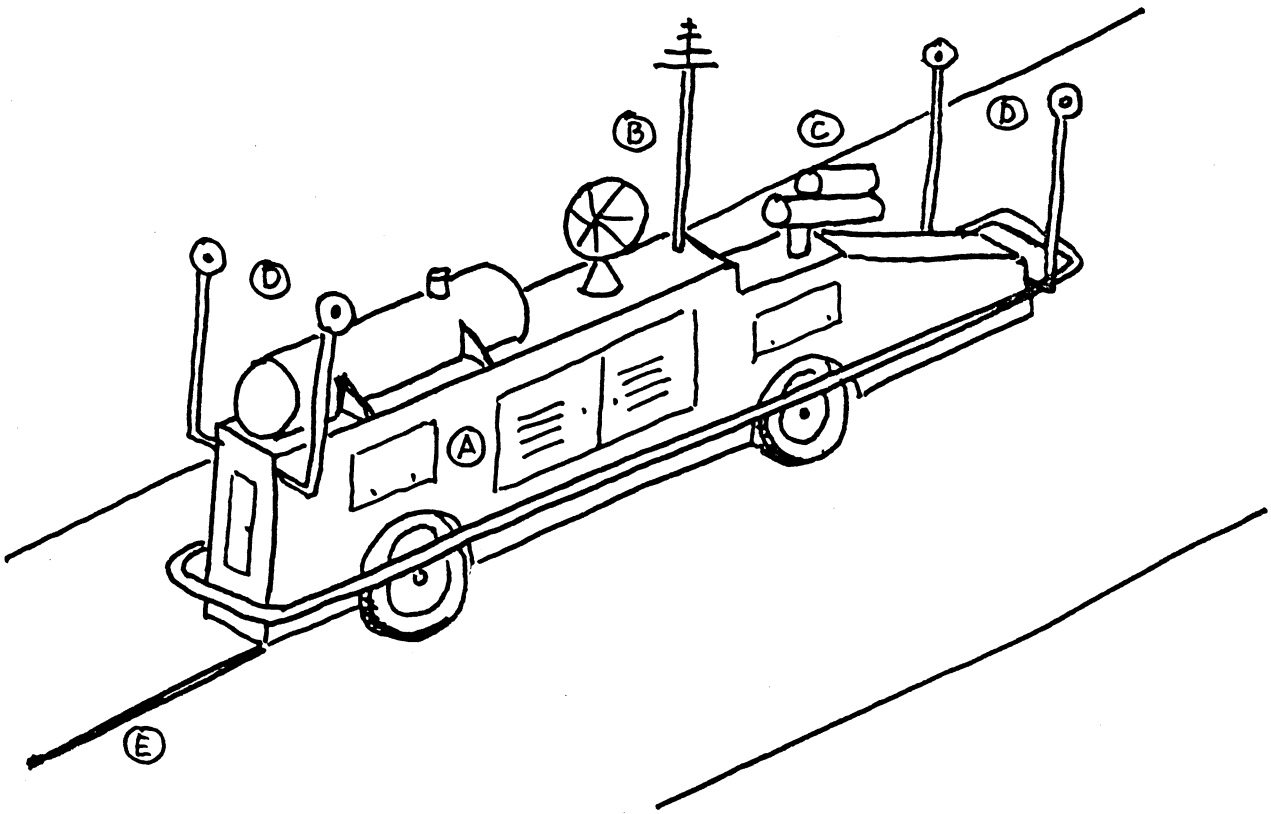
Ⓒ Multifunction handlers, gripping and securing reinforcing bars

Ⓓ Bin of stacked reinforcing bars

Ⓔ Moveable anchor frame

Ⓕ Computer console

Road Striping Robot



Ⓐ Self-propelled vehicle equipped with automatic mechanical striping apparatus

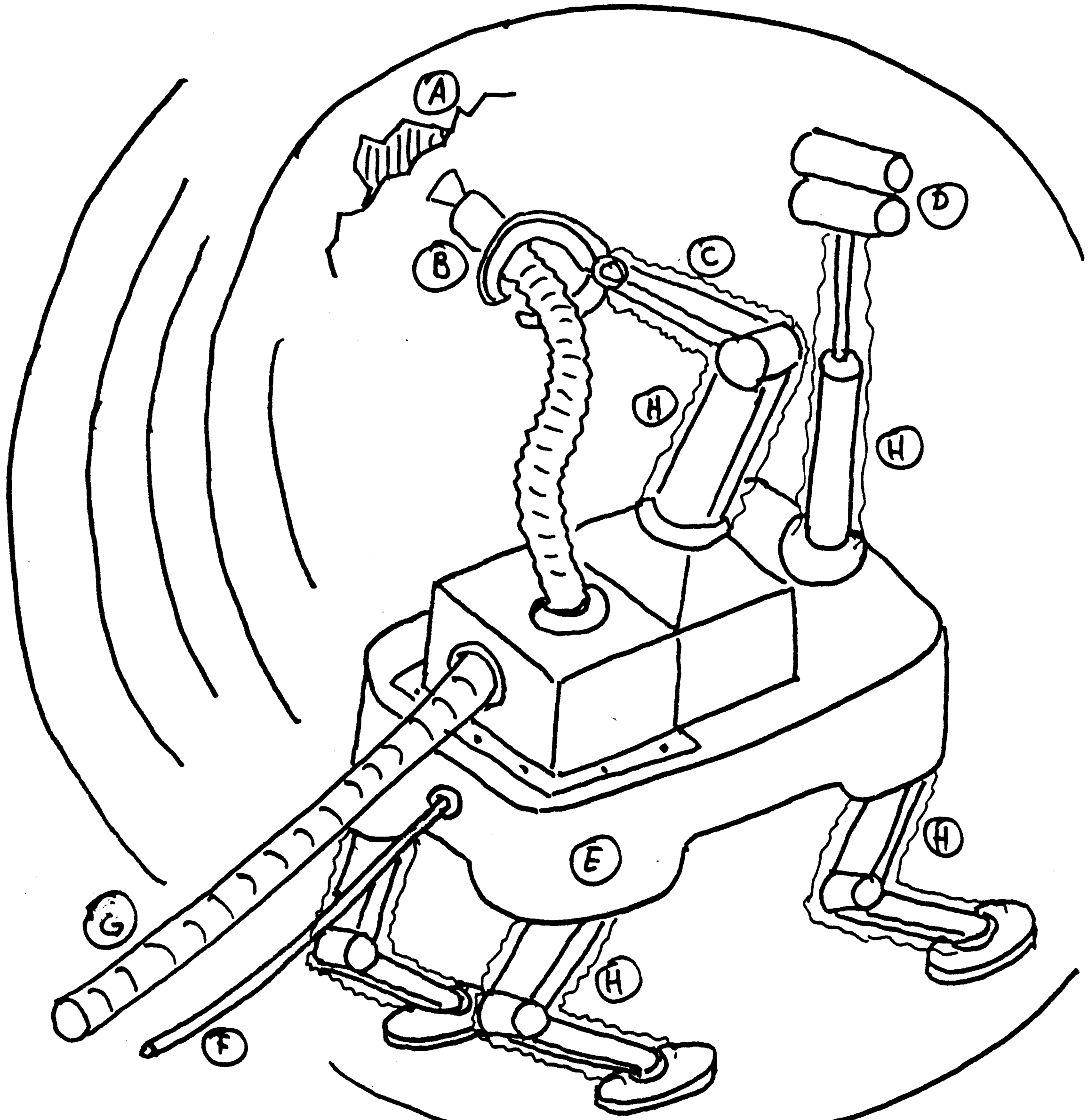
Ⓑ Guidance and communication antennas

Ⓒ Video camera and light

Ⓓ Safety lights

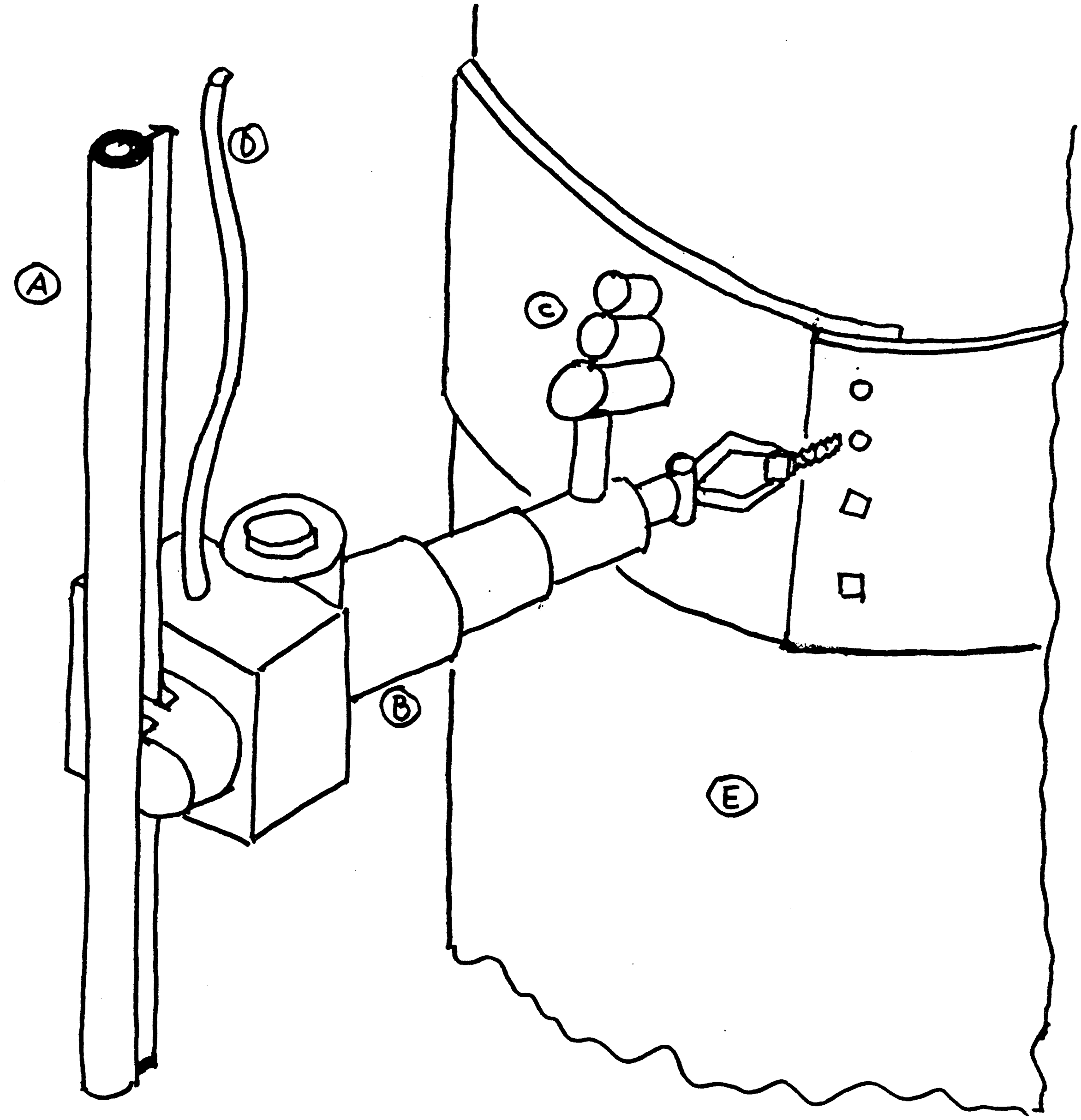
Ⓔ Stripe applied to roadway

Culvert Repair Robot



(A) Crack in culvert
(B) Flexible spray hose
(C) Remotely controlled robot arm
(D) Video camera and light
(E) Locomotive platform
(F) Power and communication cable
(G) Material supply hose
(H) Protective flexible jacket

Underwater Bridge Repair Robot



(A) Temporary post and guide rail

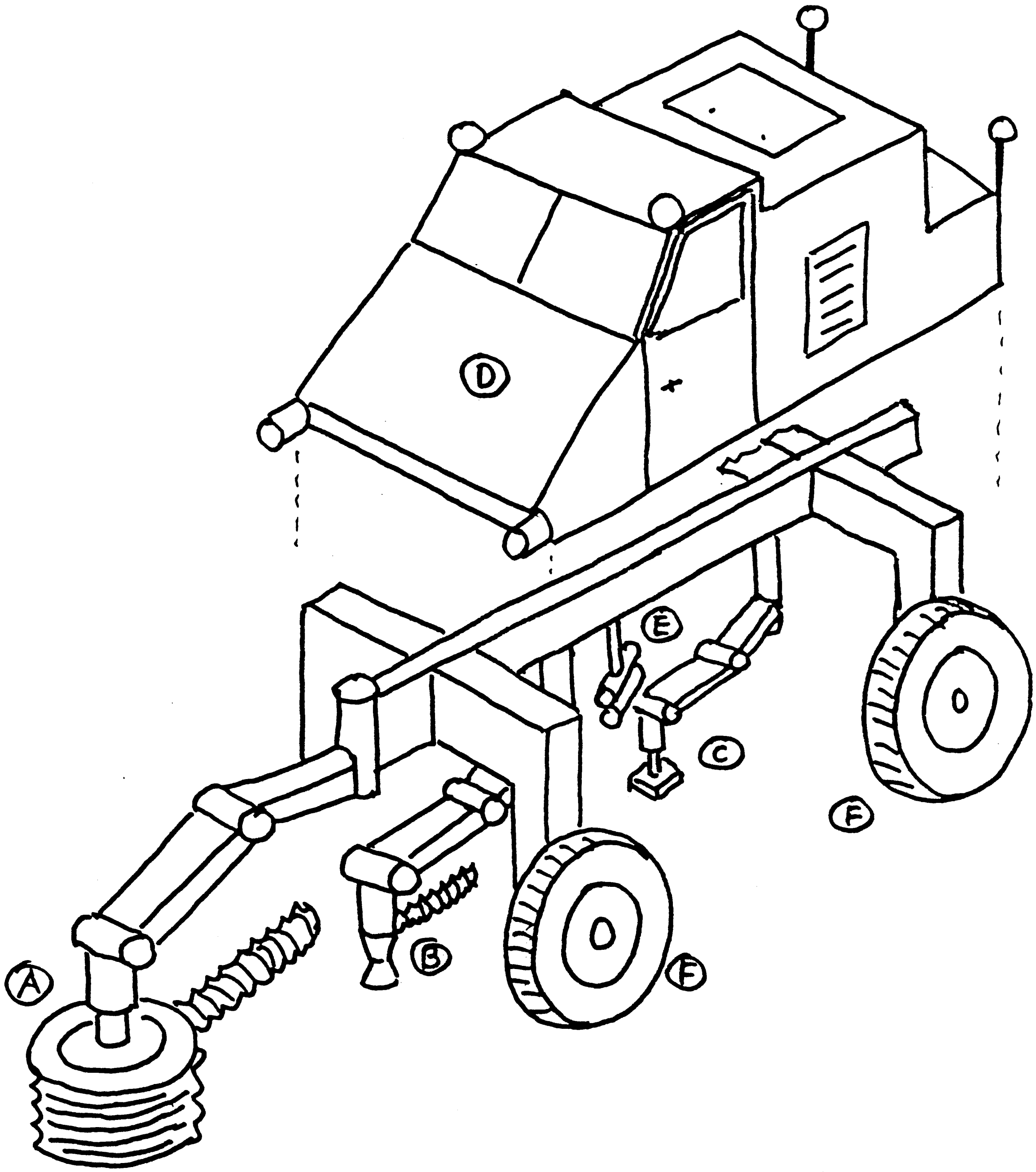
(B) Telescoping robotic arm, riding on guide rail

(C) Image enhanced video camera, light and sonar scanner

(D) Power and communication cable

(E) Underwater portion of bridge being repaired

Robotized Pothole Patcher



Ⓐ Robotized hole exciser, with vacuum hose

Ⓑ Robotized hole filler, with materials hose

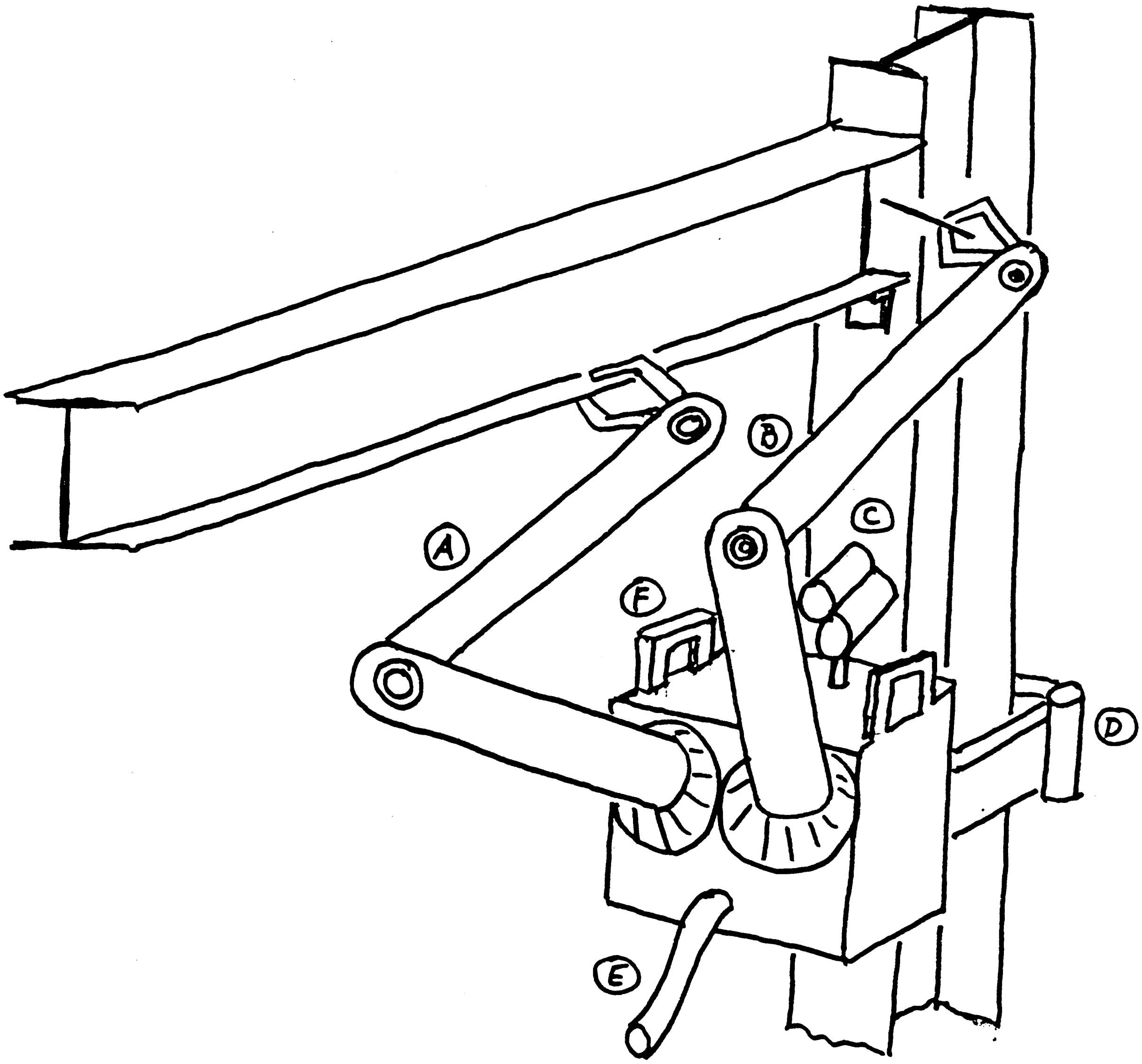
Ⓒ Robotized screed / tamper

Ⓓ Cab for operator, computers, power, materials, etc. (shown in exploded position)

Ⓔ Video camera and light

Ⓕ Electrically driven wheels, moving the vehicle units Ⓐ, Ⓑ + Ⓒ successively over the pothole

Structural Fastening Robot



(A) Remotely controlled positioning arm, holding attaching member

(B) Remotely controlled fastening arm, shown with welding rod

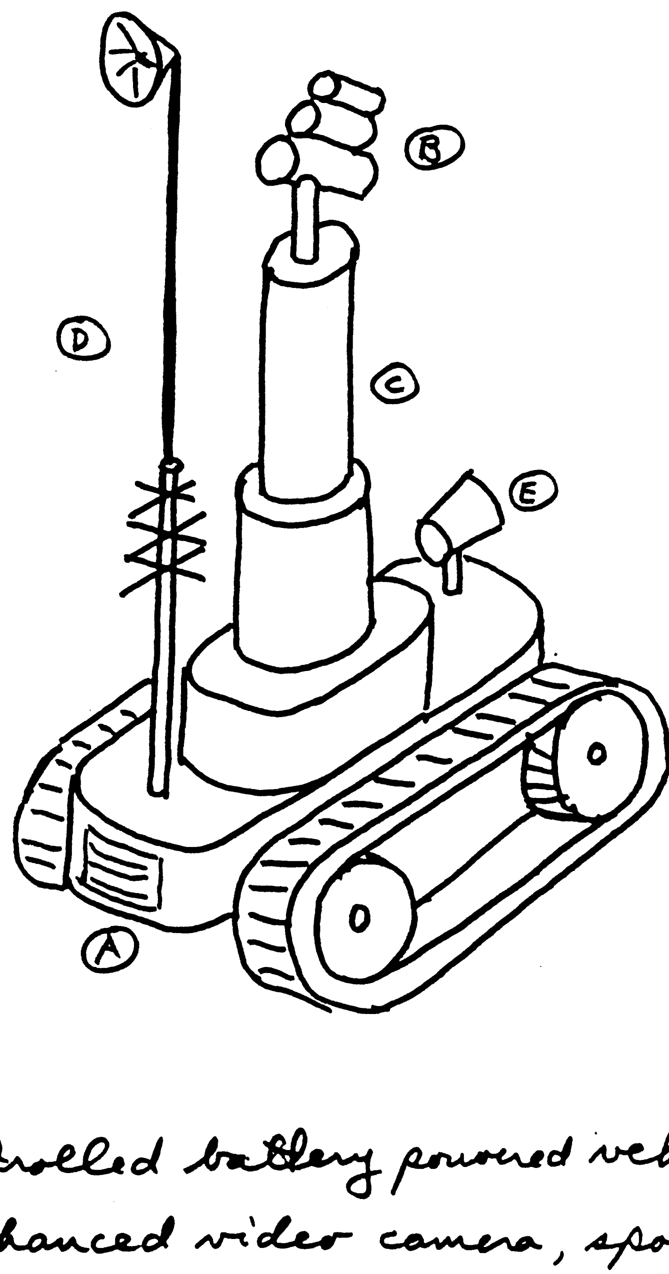
(C) Video camera and light

(D) Clamping arm, attached to fixed member

(E) Power and communication cable

(F) Lifting hooks

Roving Sentry Robot



Ⓐ Computer controlled battery powered vehicle

Ⓑ Image enhanced video camera, spot light and directional microphone

Ⓒ Telescoping periscope

Ⓓ Communication and guidance antennas

Ⓔ Loud speaker