CONSTRAINTS ON THE DEVELOPMENT OF ROBOTS FOR CONSTRUCTION

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SUMMARY

The potential for use of robots in construction, agriculture, mining, undersea and space is presently being explored in research and prototype systems. This paper reviews the history and justification for this development including consideration of both technological and economic constraints. The current worldwide status of implementation of robots in construction is reported.

As an illustration of how robots will be used in any of these unstructured environments, the application to building construction is reviewed in detail. Robots may simply evolve into traditional construction practice as another new tool. Conversely, the entire construction process can be changed through the use of robots. The underlying and principal constraints on this revolutionary process are defined along with the benefits expected from robotized construction.

Other areas for the impact of computer technology in construction include CAD-CAM and knowledge based expert systems. Their potential is discussed.

1 INTRODUCTION

Applications of robotics outside of the factory have been very limited to date but the potential in agriculture, mining, undersea and space as well as in construction is widely recognized. Construction is in many respects an ideal place for use of robotics. The construction process and environment are generally hazardous. Access to the workplace is often severely constrained and many jobs could be done more effectively if the capability to do work could be applied in places like the interior of pipe networks or on the superstructure of structural trusses. If the mass and size limitations of the human worker were not a limitation, prefabrication elements could be much larger and more efficient. For example, if a standard brick or block could be increased in size, the cost of ordinary masonry walls could be cut dramatically.

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Construction work can be repetitious and physically demanding for workers. Even without the special hazards associated with falls, large masses and the equipment used on a construction site, the routine exposure to the weather and dirt of construction is undesirable for workers. In some countries, notably Japan [36], the attractiveness of construction work has decreased to the point that severe labor shortages are forecast in the near future.

There are, however, some obvious limitations to the direct transfer of robotics technology from manufacturing to construction. Construction tasks are not highly repetitive nor are the tasks well formed spatially. The construction workplace is not well described and, in many cases, is temporary so that no stable framework exists as a reference for robots or other machines. Much of the human contribution to present construction practice is used to overcome this absence of structure. The construction workplace also can be hostile to robots where mechanical components must be built to withstand the dirty environment.

1.1 CONSTRUCTION COSTS AND PRODUCTIVITY

Economics is often cited as the principal motivation for developing robotics [47]. In the United States construction is the single largest industry accounting for about 8% of the Gross National Product. Its employees constitute about 6% of the total labor force and its workers are about 10% of the total blue collar workers in the United States. Private investment in construction accounts for 40% of the total private domestic investment (Table 1). Construction is also one of the least efficient industries as evidenced by its productivity decline (1.5% annually), low output per worker (lower by 40% than industrial average) and slow technological change. Mining and other areas of potential application for robotics outside of manufacturing also have these economic characteristics (Table 2). Because construction work is strenuous and often performed under harsh conditions, labor costs are high as reflected by wages which are 50% higher than the industrial average, high insurance rates and large economic losses due to work accidents.

This combination of scope and inefficiency creates a tremendous potential for technical innovation with promise for productivity improvement. The potential is probably highest in building construction which accounts for about 70% of the total construction value. Building construction is composed in large part of fairly homogeneous projects, and is, at present, highly labor intensive. Employment of robots which can perform building tasks, move, and interact with the environment deserves serious consideration.

Table 1: Construction Industry in the US Economy*

Year	1979	1980	1981	1982
Construction value				
millions of dollars	230,413	230,749	238,200	232,000
as % of the GNP	9.5%	8.7%	8.1%	7.5%
as % of domestic private investment	42.8%	43.7%	39.2%	38.5%
Construction employees				
in thousands	6,437	6,215	6,060	5,756
as % of total employed	6.5%	6.3%	6.0%	5.8%
Construction workers				
in thousands	3,565	3,421	3,261	3,004
as % of blue collar workers	10.9%	10.9%	10.4%	10.1%

* Source: U.S. Department of Commerce, Statistical Abstract of the United States.

Table 2: Productivity Growth in U.S. Industries: 1974-1982*

Industry	Output per person in 1982 (in 1972 dollars)	Annual change rate 1974-82
All private industries	16,660	0.9%
Agriculture, forestry, fishing	14,258	3.3%
Mining	19,258	-4.3%
Manufacturing	18,100	1.7%
Transportation	15,978	-0.9%
Communication	42,624	4.8%
Electric, gas and sanitary services	41,198	0.3%
Services	10,140	0.4%
Construction	10,059	-1.5%

* Source U.S. Department of Commerce, "U.S. Industrial Outlook 1984"

1.2 CONSTRUCTION QUALITY

Another motivation for developing automated, computer-based systems in construction is improved quality of the product. When quality is defined to include reliability, manufacturability, constructability, minimum life-cycle costs and customer satisfaction, this objective is not the present basis for decision-making in design and construction. In other industries, however, quality has become the focus. When quality becomes a principal issue in competition the impact on those who do not rapidly pursue higher quality can be very severe. The U.S. automobile industry, for example, now requires protectionist legislation to offset the quality differential with some Japanese and European manufacturers. Competitive construction, especially international construction, will soon be faced with these same issues of quality. In fact, higher quality is identified by Japanese constructors as one of the major incentives for developing robotics for the construction site.

1.3 HISTORY

The history of serious efforts to develop robots for construction is really only a few years old. Progress in Japan has received the greatest attention and the effort is impressive because essentially all of the major construction companies in the country are involved. The levels of commitment to research and development appear to range from 0.5 million dollars per year to more than 6 million dollars per year for these individual companies. Japanese work on construction robotics began about six years ago (1978) and is just now progressing from experimental research to practical prototypes. In European countries and in the United States, research and development of construction robotics is essentially confined to a few government laboratories, university research groups and industries. There is nothing like the widespread effort in Japan. Particularly noteworthy is the fact that the larger construction companies have not begun any major efforts in development of robots for use in construction (except for applications to tunneling).

1.4 SCOPE

The scope of possible applications of robotics in construction is very broad. The greatest incentive at present appears to be for applications in hazardous environments such as nuclear reactors, toxic and hazardous waste sites, fires, etc. Applications which extend beyond human capability are also attractive. Undersea and space construction and mining are likely to be the focus of major government research and development efforts in the near future. The greatest potential market for construction robots, however, is in the normal building construction and heavy construction industries. Here robots offer the potential for both productivity increases and for fundamental change and improvement of the construction process.

Along with the growth of applications for robots in construction is the more general potential for use of computers in the unstructured environment. CAD-CAM and knowledge based expert systems may have as much impact as do robots and it is likely that this impact will occur sooner and be more widespread.

1.5 ECONOMIC EVALUATION OF ROBOTS

There are essentially no data to describe the costs and benefits for use of robots in construction. For applications in hazardous environments and in problems which extend beyond human capability, an economic assessment is difficult because of the subjective nature of the benefits. The one area where an economic evaluation may be feasible is building construction where robots can decrease costs and increase productivity on items which are a normal part of the construction process.

As part of a comprehensive study of robotics in building construction, Warszawski [48][49] has attempted to define the value of a construction robot under various conditions. He considered not only the normal costs and benefits but also the significance of such factors as:

- cost of construction hazards
- loss of productivity in harsh climates
- the effects of overtime
- the benefits of quality
- a variety of environmental factors

The conclusion of this study was that the value of a robot with a 3-5 year lifetime was more than 250 thousand dollars if used appropriately. When external factors such as those listed above cause a decline in labor productivity, the value of a construction robot is even higher as noted in Table 3.

For all of these new technologies there are great uncertainties about cost and benefit. At present the major constraints on implementation of robots in construction are technological but, as these barriers are overcome, the significance of economics, labor reaction and social impact must be addressed.

Table 3: The Change of Robot Value Under Declining Labor Productivity

Decline in labor productivity* (%)	Robot value to user ($)** i = 7%	i = 1·%	Increase in value (%)
0	261,000	229,000	-
10	298,000	262,000	14%
20	336,000	295,000	29%
30	373,000	328,000	43%
40	411,000	361,000	57%

* With reference to normal conditions which assume 1.5:1 robot to worker ratio.

** Assuming 1,500 employment house per year, and 5 years economic service life.

2 CURRENT LEVELS OF APPLICATION

The current worldwide use of robots (estimated to be 30,000) is almost entirely directed toward industrial applications. The principal activities are [48]:

- machine tool processing
- welding
- palletizing
- paint spraying
- inspection
- assembly
- casting and forging
- loading and unloading

These operations are well documented in [3], [9], [18], [20], [40], [41] and in current trade publications. About one half of these applications involve simple "pick and place" operations, and less than 10% of those use sensors for interaction with the environment.

Commercial applications of robots to construction are almost nonexistent at present. Several robots, most of them of an experimental nature, were developed and employed in Japan, the United States and Europe. These applications are briefly reviewed below. Some of them do not exactly conform to the most narrow definition or robotics. However, they are defined as such by the sponsors and certainly contribute to the advancement of robotization in building.

1. *Shotcreting robot*: the robot uses a shotcreting gun effector, mounted on an arm of a conventional earth excavator (can also be mounted on other equipment). The gun covers a certain wall area by revolving from a static position, and is moved by the arm from one location to another with manual control. The robot is described in [25].

2. *tunneling robot*, which employs rotating blades for earth excavation, and a pressure concrete system for wall stabilization during the tunneling. The robot's operation is controlled through feedback from earth pressure gaging sensors mounted near the blades. The system is described in [25].

3. *concrete distributing robot* (described in [26]). The robot employs an articulated long arm for supporting a concrete pump hose. The arm is controlled by a human operator.

4. *fireproofing robot* (described in [46]) - employs an articulated arm with a spraying gun. It moves from one location to another guided by a magnetic wire. Its operation at each location is preprogrammed.

5. *drilling robot* (described in [45]) is used for tunneling work in a rock stratum. The drillers are numerically controlled and their mode of operation is controlled while gaging the rock hardness.

6. *tile inspecting robot* (described in [11]) moves vertically on an external wall and measures by acoustical response the adhesion of tiles to the wall surface.

7. *remote reconnaissance robot* (described in [50]) is a teleoperated vehicle for hazardous environments which can move, collect information and relay it back to users. This robot is currently being used to assess the damage in the underground area of the Three Mile Island nuclear power plant.

8. *reinforcement mapping robot* (described in [27]) is an automatic carriage which, by using electromagnetic sensors, can detect and map concrete embedded reinforcement. The robot is now in its final stages of development.

9. *excavating robot* (referred to in [33]) which uses a mechanical probe and an array of sensors to discover utility pipes buried underground and uncover them if needed. This robot uses a robot controlled sensing and imaging system [22] for subsurface vision.

10. *heavy duty manipulator* (described in [21]) designed for various manipulation tasks in severe environments. Rock drilling machines have been a principal application.

11. *tree harvesting robot* (described in [21]) is an adaptation of the heavy duty manipulator for harvesting and field processing of timber products.

Several other possible applications of robotics have been discussed for demolishing [25], reinforcement preparation and positioning [16], formwork, and other subjects [15] [17].

3 ROBOTICS IN BUILDING CONSTRUCTION

If robots are to be developed for applications in construction and other unstructured enironments, the technology of robotics in manufacturing must be modified to meet several different constraints. Industrial applications are characterizd by fixed-position robots that perform highly repetitive tasks in an assembly line format. In contrast, construction tasks demand robotic capabilities to address quite different issues including [36]:

- mobility around the job site
- an unstructured work environment posing complex problems of objective sensing and spatial control
- forces that are larger by one or more orders of magnitude than those associated with industrial robotics
- unstructured tasks that are both poorly configured and much less repetitive than those in the factory environment.

It is also reasonable to expect that the construction process will change dramatically in response to the potential of robotics. Anticipating the specifics of these changes is difficult, however, as part of the work of Carnegie-Mellon's Robotics Institute, Warszawski [48] has conducted an extensive analysis of applications to the building construction industry. Since buildings are the objective of 70% of current construction efforts, this study is of interest. The general observations and conclusions also may be applicable to other unstructured environments. The basis for applying robots to building construction is existing *robot technology*. This technology can be applied only if *building construction activities* are understood. These two elements lead logically into *robotization of the building process*. As an illustration of this process, a summary of Warszawski's work is useful.

3.1 ROBOT TECHNOLOGY

A general description of robot characteristics, performance and applications may be found in [9],[15],[18],[41],[47] and other sources. Detailed comparisons of human vs robot characteristics have also been reported [9]. This basic work defines the attributes of robots which are of interest in their application to building construction. A robot for building construction can be defined as a defice which will perform a sequence of production tasks without direct human intervention (for an extensive discussion of various robotics definitions used in the United States and Japan, see [10] and [18][19]). Typical tasks may involve hauling of objects from one place to another, or their processing (painting, drilling, welding, etc.) with appropriate tools. For performance of these tasks the robots can be completely preprogrammed, "taught on site" by the operator, remotely controlled, or preprogrammed and allowed to modify their performance according to the perception of the environment obtained through sensing devices. They may perform their tasks with an aid of one or more arms, from fixed positions, or moving around. The attributes of robots which are important from the construction view point are their manipulation, effecting, control, sensing, and mobility capacity.

3.1.1 Manipulators

Most robots manipulate or handle different objects with an arm which can reach (and place) them at any location in space and a wrist which can orient them as desired. Several examples of more common manipulation systems are show on Figure 1a (three axial translations in rectangular coordinates), Figure 1b (rotation and biaxial translation in cylindrical coordinates), Figure 1c (two axial rotations and translations in polar coordinates), Figure 1d (three axial rotations in revolute coordinates). This last configuration, referred to also as jointed, articulated or antropomorphic, is most widely used today in industrial robots. The orientation is performed by rotating the wrist around three perpendicular axes (yaw, roll and pitch) as shown on Figure 1e. An extensive survey of the various types of robot manipulators in use today is included in [9],[19],[41],[42],[43] and others.

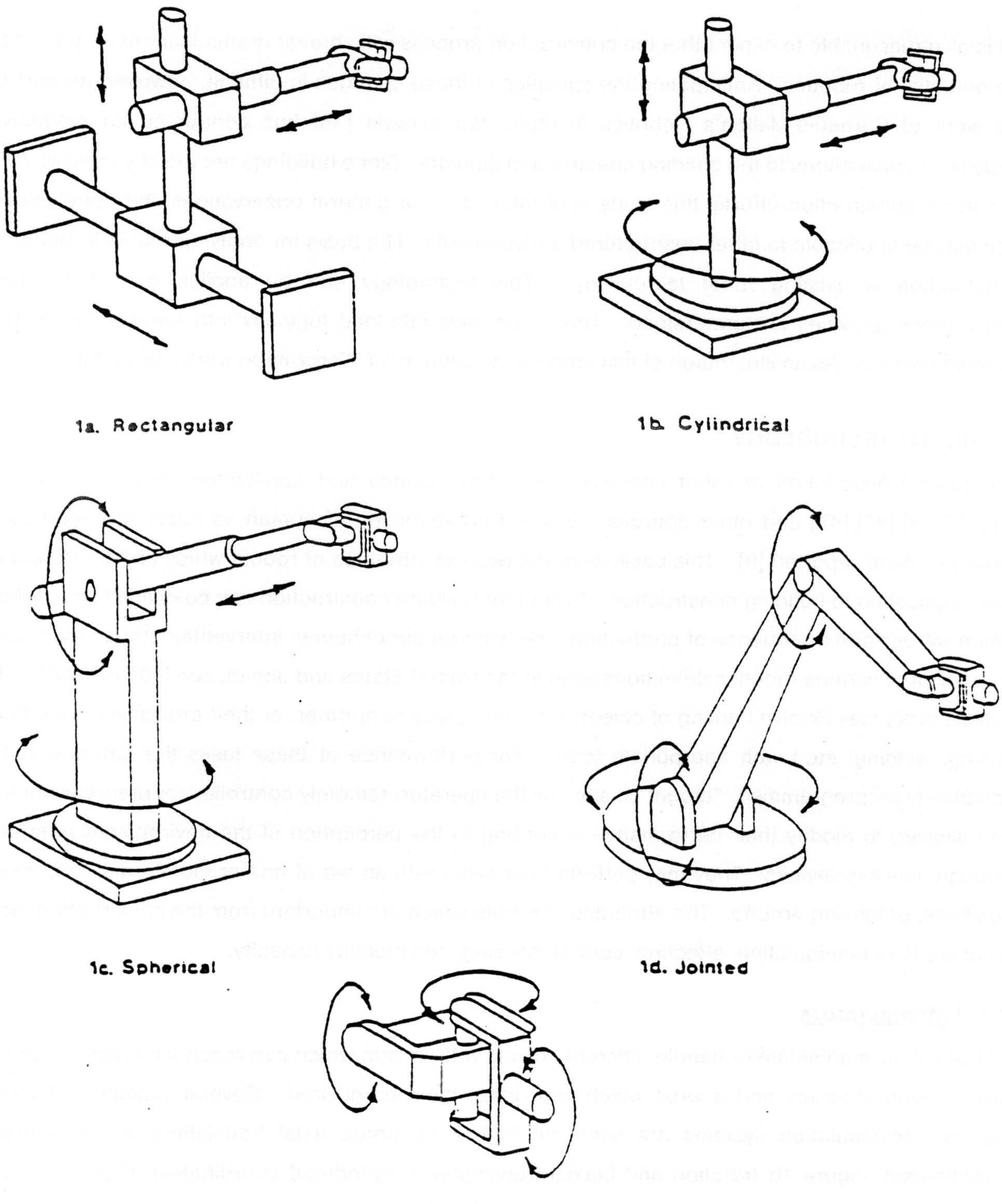

Figure 1: Typical configurations of industrial robots

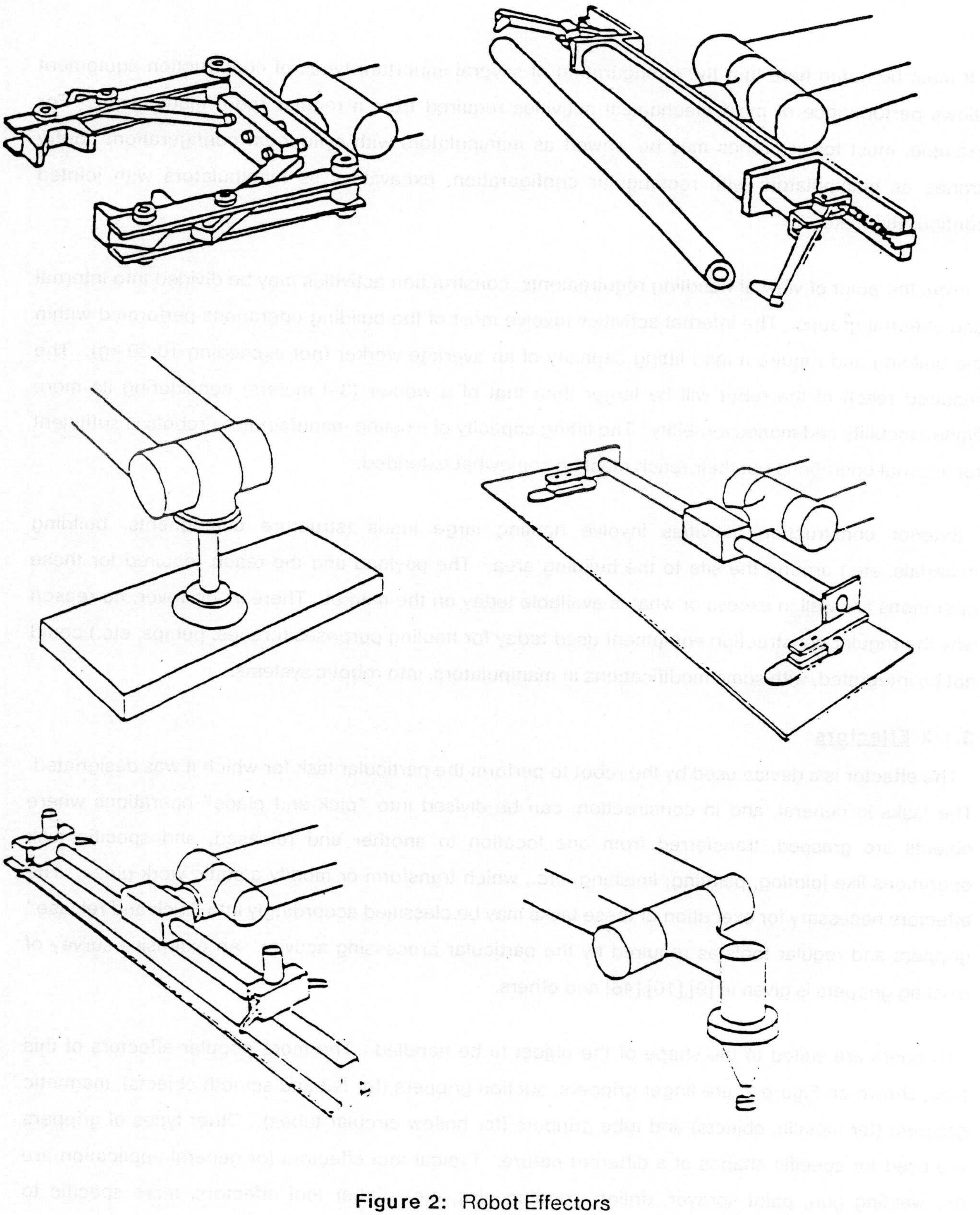

Figure 2: Robot Effectors

It must be noted here that the configuration of several important types of construction equipment allows performance of most mechanical activities required from a regular robot manipulator. For example, most tower cranes may be viewed as manipulators with cylindrical configuration, gantry cranes as manipulators with rectangular configuration, excavators as manipulators with jointed configuration, etc.

From the point of view of handling requirements, construction activities may be divided into internal and external groups. The internal activities involve most of the building operations performed within the building and require a load lifting capacity of an average worker (not exceeding 10-30 kg). The required reach of the robot will be larger than that of a worker (3-4 meters) considering its more limited mobility and maneuverability. The lifting capacity of existing manufacturing robots is sufficient for internal operations but their reach must be somewhat extended.

Exterior construction activities involve hauling large loads (structure components, building materials, etc.) around the site to the building area. The payload and the reach required for these operations are well in excess of what is available today on the market. There is, however, no reason why the regular construction equipment used today for hauling purposes (cranes, pumps, etc.) could not be integrated, with some modifications in manipulators, into robotic systems.

3.1.2 Effectors

The effector is a device used by the robot to perform the particular task for which it was designated. The tasks in general, and in construction, can be divised into "pick and place" operations where objects are grasped, transferred from one location to another and released, and specific task operations like jointing, painting, finishing, etc., which transform or modify a static work piece. The effectors necessary for execution of these tasks may be classified accordingly into "pick and release" grippers and regular tools as required by the particular processing activity. An extensive survey of existing grippers is given in [9],[10],[48] and others.

Grippers are suited to the shape of the object to be handled. The more popular effectors of this type, shown on Figure 2, are finger grippers, suction grippers (for flat and smooth objects), magnetic grippers (for metallic objects) and tube grippers (for hollow circular tubes). Other types of grippers are used for specific shapes of a different nature. Typical tool effectors for general application are the welding gun, paint sprayer, driller, grinding disc, etc. Other tool effectors, more specific to building operations, could be used for spreading of glue, mortar and concrete, for sealing of joints, troweling, smoothing, sand blasting, taping, bolting, vibrating, etc.

Most effectors are positioned and oriented by the manipulator, and their operation is triggered by an on/off command of the control unit (grasp/release; act/stop). Some effectors may be activated directly through sensors attached to them. The quality of performance of the effector depends on the manipulator's positioning tolerance, the working tolerance of the tool it employs, and the performance of the sensory device if it is used to interact with the environment. These task control sensors are particularly important in construction applications [36].

Another condition for a satisfactory effector's operation is an orderly supply of material which it may use for its activity. Such supply may be readily ensured in manufacturing where the work is performed in a static, well-designed and structured work place. The problems of effector feeding in a less structured and changing work place pose difficult problems in building construction.

A manipulator's arm may employ simultaneously more than one type of effector. They can be exchanged as needed by a human operator or automatically by the robot.

3.1.3 Control

The Japanese Industrial Robots Association [19] classified robots in six groups according to the level of control or intelligence: M1 - manual control; M2A - fixed sequence; M2B - variable sequence; M3A - playback; M3B - numerical control; M4 - artificial intelligence. In construction applications, the following control types provide a useful classification.

- indirect human guidance (teleoperation) (M1). This mode of operation is already applied in construction with reference to remotely controlled cranes, concrete pumps, and excavating equipment. Teleoperated control is discussed in [37].

- a fixed sequence of steps build into a robot mechanical system (M2A).

- a preprogrammed sequence of steps which may be changed from task to task (M2B). In most cases the control unit "learns" the desired sequence of arm movements when the arm end is guided by the operator on the path of its intended activity (M3A) (spraying, welding, etc.). Another possibility is to preprogram the complete set of instructions in a computer language which the control unit understands (M3B). The methods of robot programming are explained in [4];[31],[35].

- a preprogrammed sequence of steps which can be modified through interaction with the environment (M4). The signals from the environment are input into the control unit with the aid of transducers which act in a way similar to human senses: vision, contact, hearing. Interpretation of these signals and a consequent planning of activity requires a degree of "artificial intelligence" built into the robot control. In more involved cases, the amount of computation necessary to put this intelligence to use requires considerable processing time and memory capacity. Various methods of artificial intelligence are described in [10],[14],[51] and others.

The fixed sequence mode of operation has a very limited application in construction in view of ever-changing tasks and an unstructured workplace. It may be of use, however, in the various building materials industries where robots can perform repetitive, simple tasks within a static and well structured production line. A rigidly preprogrammed mode without human supervision or continuous feedback from the environment will be of limited use in today's construction operations, considering the complexity of the building tasks, the rugged site conditions and the high tolerances of most infrastructure components. It may be possible, however, to preprogram robots for execution of homogeneous and well-structured portions of large tasks like painting, concreting or building. The boundaries of the work segments to be executed will be "learned" by the robot on the spot and "played back" by its control system during the execution. This type of cooperation may be achieved within the framework of combined man-robot teams where robots perform the standard simple tasks within defined boundaries, and humans engage in work planning, guidance, and execution of more involved finishing operations.

3.1.4 Sensors

The highest level of robot self-control (M4) is attained when the contol unit can modify a manipulator's activity based on the information received from the environment during its performance. The information is received through "sensory" transducers which convert various physical effects (mechanical, optical, electrical, acoustic, magnetic, etc.) into electronic signals which can be recognized and acted upon by the control unit. Various types of transducers and the principles of their operation are described in [1],[6],[12],[13],[29],[30],[36],[42],[44]. Future needs are discussed in [12],[29],[36].

Sensors are very important to robotization of building operations because they can convey to the control unit, in real time, the main features of ill-structured and changing building environments. The more important groups of these devices in the building construction context are the tactile, proximity and vision sensors. *Tactile* sensors may merely indicate a contact with an object or may relay the extent and the direction of force exerted during the contact. *Proximity* sensors detect proximity of objects, and may also indicate their location and range. Vision sensors react to light reflected from objects, with ensuing signals being later translated into images, with the aid of artificial intelligence.

The employment of sensors in construction robots may be required in the following instances:

- prevention of collision between the robot's arm or body (in case of mobile robots) and an object to be handled or a part of the structure. The contact or its imminence is sensed by an appropriate transducer, which then sends a warning signal to the motion control unit.

- verification of the required preprogrammed work path in welding, taping, jointing, etc.

This can be achieved by a contact sensor (strain gage or potentiometer) if the effector can follow an edge of an existing component. Deviation of the effector from the prescribed path will result in a change in interacting forces between the sensor and the edge which will send, in turn, a signal to the control unit. Another type of sensor which will monitor effector movement is a light detecting diode, reacting to luminescent markings prepositioned on the desired path. Finally, the movement may be monitored by a vision camera transmitting the image of special features, to which the desired effector path could be related.

- verification of work quality and its conformance to specifications. This task can be performed with the aid of proximity (ultrasonic or electromagnetic) sensors when inspecting the thickness of coating, and contact sensors, when inspecting smoothness of surface. Vision sensors can be used for inspection of texture and exterior dimensions of a component.

- navigation of a robot's arm or body towards a desired point. This can be attained with vision, or a variety of other sensors. Strategies employing both passive sensing and active sensing have been proposed for construction applications [36].

3.1.5 Mobility

Almost all robots employed in industry today operate from fixed positions. The work pieces are brought to them by means of conveyors and other devices. In construction the location of work changes continuously and therefore the robots in any type of employment must also move, or be moved, from one location to another.

The physical configuration of a moving robot will be somewhat different from fixed-base industrial robots. The mostly experimental models of moving robots constructed to date have used wheels, treads or legs for their locomotion. Robots can be transferred from one work station to another with direct or remote human control. In ideally structured environments, the robots can be preprogrammed to follow a desired path. In real-life construction work the roughness of the surface, imprecision of dimensions, and possible obstacles on the path require continuous interaction with the environment. This can be done by employing sensors which can record specific features of the environment - walls, corners, openings, etc. The features are compared, with the aid of computer intelligence, to the preprogrammed representation of the environment and the program is modified on the basis of discovered discrepancies.

Navigation may be greatly simplified by guiding the robot along its path with a prepositioned electric wire (sensed with electromagnetic sensors) regular wire (sensed with potentiometer or strain gage), etc. The present experience with mobile robots and their control algorithms is described in [5],[23],[24],[35],[39],[51].

3.2 BUILDING CONSTRUCTION ACTIVITIES

Building construction activities can be separated into several lists to consider the potential for robotization. Warszawski [48] divided the building into these major components:

- substructure
- framing
- horizontal space dividers (floor-ceilings)
- exterior walls
- partitions
- experior wall finish
- interior wall finish
- flooring
- roofing
- mechanical and electrical systems

The prevailing alternatives for construction of these components were then systematically examined and analyzed for their possible adaptation to robotics. Based on this analysis the specific tasks of building construction were divided into 11 basic activities, as shown in Tabe 4. These activities were defined in such a way that each of them could be performed by a single robot with the same effector and mode of operation.

Most building construction tasks require more than one type of basic activity. For example, the casting of concrete elements requires at least these activities:

- stripping of forms
- finishing of concrete

and bricklaying requires these:

- spreading of mortar
- laying of bricks
- tooling of joints

To better understand the specific details of what a construction robot would require, the performance requirements for each basic activity presented in Table 4 have been specified. This specification was defined in a uniform manner with respect to these attributes:

- manipulator's performance (reach, payload)
- effector characteristics
- feeding method (supply of materials to be used by the robot)

No.	Activity	Description	Examples of Application
1	Positioning	Placing a large object at a given location and orientation	Erection of steel beams, precast elements, formwork, scaffolding
2	Connecting	Connecting of a component to an existing structure	Bolting, nailing, welding taping
3	Attaching	Positioning and attaching of a small object to an existing structure	Attaching hangers, inserts, partition boards, siding sheathing
4	Finishing	Applying continuous mechanical treatment to a given surface	Trowelling, grinding, brushing, smoothing
5	Coating	Discharging a liquid or semiliquid substance on a given surface	Painting, plastering, spreading mortar or glue
6	Concreting	Casting of concrete into molds	Casting of columns, walls, beams, slabs
7	Building	Placing blocks one next or on top of the other with a desired pattern	Blocks, bricks or stones masonry
8	Inlaying	Placing small flat pieces one next to the other to attain a continuous surface	Tiling, wood planks flooring
9	Covering	Unrolling sheets of material over a given surface	Vinyl or carpet flooring, roof insulation, wall fabric
10	Jointing	Sealing joints between vertical elements	Jointing between precast elements, between partition boards.

Table 4: Basic Activities in Building Construction

- control of the system
- sensing capacity
- mobility

Each specified requirement was then followed by technical solution alternatives. The performance specifications and the available solutions are presented in [48]. The findings and their implications with regard to implementation of robotics in construction are of particular interest.

3.3 ROBOTIZATION OF THE BUILDING PROCESS

Implementation of robotics into construction may follow a variety of paths but these can be grouped into two principal categories. The first category involves an irregular evolution of existing construction practice and equipment. Robots will be developed and used in a variety of applications and places with local (to the job) conditions being the justification for implementation. This local justification may be a particular hazard or some unique economic factor. The expected sequence of steps in this evolution would be:

- further automation of existing construction equipment through devices such as teleoperation, limit switching, numerical control and microprocessors. This process is currently underway.
- adjustments of building technology to a higher automation level mainly through simplification of finishing tasks and prefabrication of components into assemblies for easier installation.
- development of robots especially designed for specific groups of construction tasks. The difference between these robots and their manufacturing counterparts will be primarily their load handling capacity, reach and mobility. All of these differences will require higher levels of sensing and intelligence.

In contrast to an evolutionary mode, robots may come to the construction site as part of an entirely new building system. Highly industrialized building systems have been considered for some time. Lower cost and improved building performance are cited as the principal benefits. Two factors now make this revolutionary concept more viable: robotics plus the use of CAD-CAM and extensions of computer applications into management and quality control. Robotics and CAD-CAM can bring about major changes including: new building materials and components, extensive prefabrication, flexible modular construction and vastly improved construction quality.

Whichever path is followed, and both are likely, the same principles will apply to the development.

3.3.1 Construction Robots

It appears from the analysis of basic construction activities by Warszawski [48] that almost all building construction operations can be performed by 4 basic types of robots: the assembling robot, the interior general purpose robot, the floor finishing robot and the exterior wall finishing robot. These types have certain distinguishing features in common which make them a unique class.

The Assembling Robot

This robot (shown on Figure 3a) is to be used for hauling and positioning of large building components: steel beams, precast concrete members, semi-assembled formwork, etc. The recommended manipulator for these operations is an antropomorphic arm (resembling the arm of an excavator or pumped concrete boom) with a reach of 20-25 meters and a payload of 1000-3000 kg. The arm may have 3-4 DF (degrees of freedom), with an additional 2-3 DF at the wrist for orienting and precise positioning of the elements, if used for assembling operations. The manipulator may be fixed to the structure within the building perimeter, or mounted on a mobile platform outside of it.

The effectors employed by the robot could be finger hooks, suction grippers or magnetic grippers, depending on the nature of the objects to be hauled and positioned. The objects to be handled must be very carefully stored on the site, or preferably on trucks or in containers, in a pattern easily recognizable by the control mechanism.

The robot may be controlled by a teleoperator, which seems most feasible at the present stage, or preprogrammed and monitored by sensors. The "pick and place" activities on a construction site may be facilitated by premarking components so that they can be identified and oriented by the robot sensor system. This rigging of the construction site using active sensors can overcome many difficult problems of implementing robotics in construction [36].

The robot system will be most advantageously used under conditions harsh or hazardous for human work, and will require appropriate design of the elements and the assembling process so that the need for human assistance in attaching of the elements and their orientation, bracing and temporary supporting, can be eliminated. As an alternative the robot may use an additional effector mounted on the same arm for temporary or permanent connecting of the positioned elements to the existing structure.

The General Purpose Robot

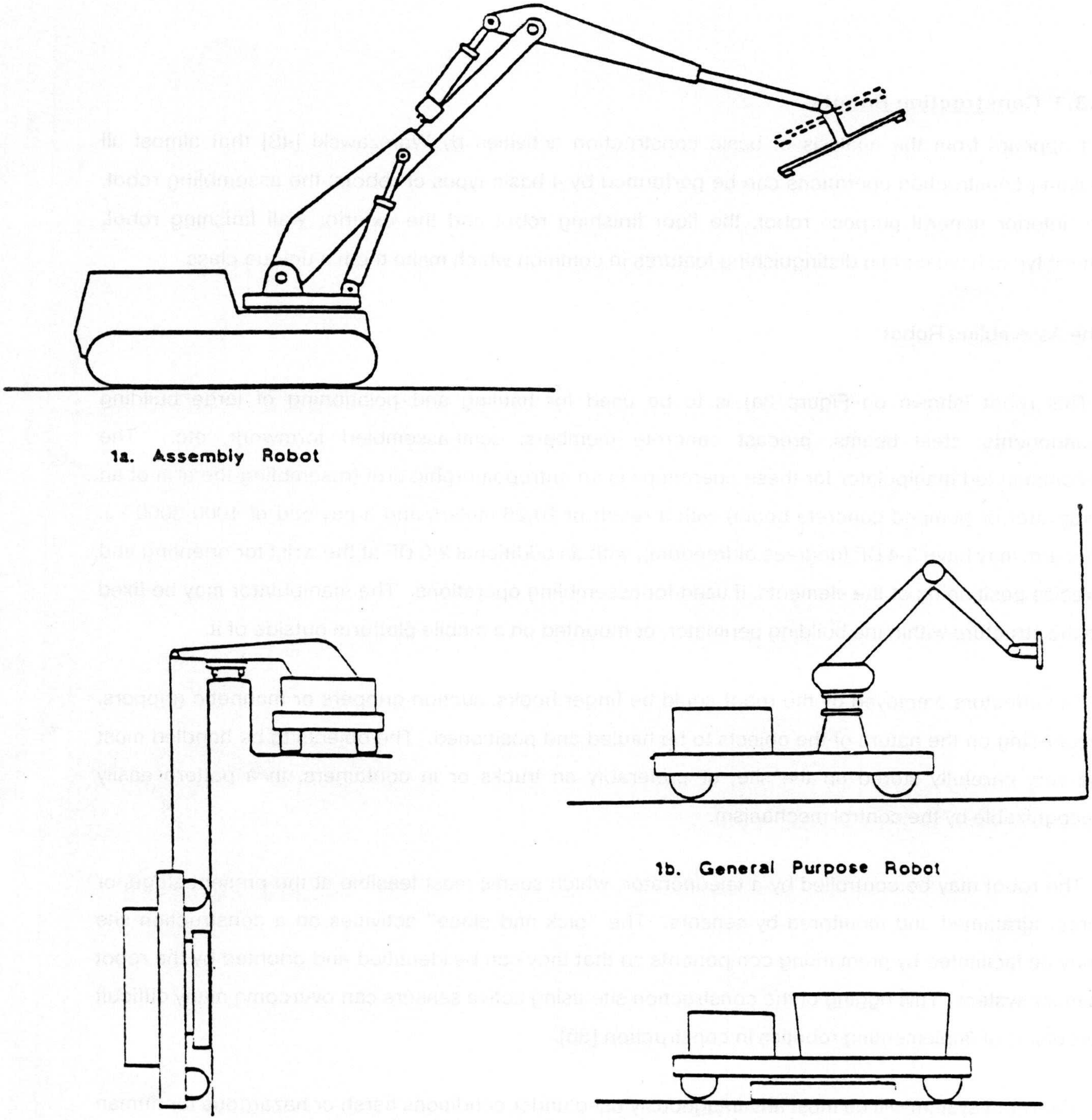

Figure 3: Construction Robots

The general purpose robot will be used for all building interior operations which can be performed from temporary static work stations. Examples of such operations are painting, grouting, nailing, bolting, etc. A schematic representation of this robot is shown on Figure 3b.

The robot will operate from a temporary fixed position and employ an antropomorphic arm with 5-6 DF, and a reach of 3-4 meters. The smaller dimension (3 meters) is the necessary minimum to reach every point on an interior wall of a usual commercial, public or residential building, and the larger (4 meters) to be able to operate from the same location over a regular roomsize area. The exact dimension for each use within this range involves a tradeoff between more frequent mobility vs higher expense for a sturdier arm. An arm in excess of 4 meters may be difficult to manipulate within the confines of a regular building.

Lifting capacity of the arm should be sufficient for the weight of the heaviest tool or interior building component - in most cass not exceeding 20 kg. Different effectors (drillers, spraying guns, grippers, etc.) may be used depending on the operation to be performed. In operations which require a continuous supply of finishing material (plaster, grout, paint, etc.), it will be supplied from a canister mounted near the manipulator and replenished periodically, or in case of liquid/semiliquid materials, pumped from an external source.

One of two possible modes of control can be used. The robot can be preprogrammed with respect to the operational pattern of the effector, or it can be "led through" the tasks it has to perform. The latter mode will be feasible for an activity performed in a building which can be divided into a large number of modular sections, or of the same work content, with each section served from a single robot station. The two modes can also be combined, with the "leading through" confined only to several critical points which define the scope of work and the rest filled in with the aid of an appropriate control algorithm. In both cases, considering the ruggedness and imprecision of the building environment, the control should be assisted by real time feedback from the operation provided by vision, contact or proximity sensors.

Transfer of the robot from one work station to the next (on wheel or tread mounted carriages) can be done manually (by a human operator), by a teleoperator, or with the aid of an automatic navigation system. The manual transfer will be feasible if the robot will be used as a "helper" by a small crew working in its vicinity. The teleoperated transfer will be most appropriate with one human operator monitoring the work of several robots employed on a single working site. The self-navigating robots use sensors, such as rotating vision cameras or sonar, with the aid of which they can detect some special features of the environment, walls, corners and openings. The workplace can also be triggered to provide a path for the robot to follow.

The main problem with a general purpose robot will be its required sturdiness which is necessary to withstand the rugged conditions of the building environment. This sturdiness must be attained with minimum weight so as to pose no special demands on the floor structure. The necessary weight can be reduced by using lightweight metals, and providing intermediate support to the robot arm during its operation.

The Floor Finishing Robot

The floor finishing robot is to be used for horizontal finishing operations, trowelling, glue spreading, brushing, etc., which involve large floor areas. The robot will consist of an effector affixed to a mobile platform and applied directly to the floor underneath. The movement of the effector (trowel, hose, gun, etc.) will be done through the movement of the carriage. Some freedom of movement of effector with respect to the carriage will be allowed to enable the finishing operations near the limits of the designated area.

The robot may be teleoperated to move over the required work area, or it can be preprogrammed and "led through" the critical points. The movement of the robot within the required area may be ascertained by using appropriate limit switches activated when contacting a temporary barrier form erected on its periphery. A schematic representation of the floor finishing robot is shown on Fig. 3c.

The Exterior Wall Finishing Robot

This type of robot will be used for finishing activities, such as painting, plastering, weatherjointing and finish inspection of large areas on the exterior of buildings. The robot will consist of a vertical carriage suspended from the roof's parapet and an effector mounted betwee it and the wall surface. The carriage will cover vertical strips, being moved up and down the wall surface while the effector moves vertically with the carriage. This robot should have some freedom of horizontal movement to cover a width of 2-4 meters. The effector may be pressed towards the wall surface using vacuum grippers attached to the carriage.

An exterior finishing robot may be controlled by a teleoperator, or preprogrammed for the desired task and performed area, and monitored by the feedback from vision, or contact sensors. A schematic illustration of the exterior wall finishing robot is shown on Fig. 3d.

3.3.2 Robotization of Building Activities

The building construction activities analyzed by Warszawski [48] can be divided into three main groups:

- Activities which involve *covering* or *conditioning of continuous surfaces*, such as painting, spraying, plastering, trowelling, screeding, spreading of mortar, cleaning, polishing, grinding, sandblasting, etc. These activities can be performed, without any difficulty, at the present stage of technology with the types of robots described above.

- Activities which involve *moving* the *effector* to different locations in a *predetermined pattern*, linear or point to point, in order to accomplish the required task (e.g. welding, bolting, taping, jointing, grouting, spreading or resilient material rolls, etc.). These tasks can also be accomplished without particular difficulty at the present stage of technology if a sufficient precision can be achieved both in the dimensions of the structural elements to which the tasks are applied and in the access points of the robot from which it commences its task. Since these conditions cannot be assured with the present building conditions, the robot can be usefully employed only if guided by humans, or equipped with sensory devices to monitor its performance. The available sensors are not yet entirely dependable in the rugged environment of building construction. It may be expected however, that with the present rate of progress in robot technology, dependable sensory devices could be developed within a short period of time if specifically defined and economically justified by the prospective demand.

- Activities which involve *handling, positioning* and *assembling* of large and small building components like structural steel, precast elements, timber planks, formwork, scaffolding, sheathing, siding, tiles, pipes, etc. These activities are most difficult for robotization because they involve very precise storage of often bulky components, their careful multi-axis manipulation and accurate orientation and positioning. A robotic system necessary to satisfy these requirements must be quite involved and costly. On the other hand, some activities in this category, in particular the assembling of framing steel and precast concrete elements constitute the very core of building construction operations and simply cannot be omitted from robotics considerations. In fact, for economic reasons (explained in [48]) the highest benefits in the building construction field can be obtained from the robotization of these activities.

Construction of many building components requires several activities such as positioning and finishing. Masonry, plasterboard partitions, and siding, are examples of such components. Technically, they can be constructed by robots, however, the programming and installation for each particular case will be so involved and resource consuming that the feasibility of implementation is very doubtful. Therefore, to make the application feasible, it is necessary to delegate as many positioning, connecting, finishing, and joining activities to off-site preparations and to utilize on site ready-made comprehensive assemblies. Such components should be easy to handle, self-supporting and readily connectible to the structure.

The following conclusions can be drawn with respect to robotization of the building construction activities:

- the numbr of elements to be positioned should be minimized. This can be achieved by using large prefabricated comprehensive assemblies. Small elements (planks, boards, tiles, bricks) should not be used in robotized activities, except when preassembled in the factor into the largest possible components.

- the components should be designed in such a way that their configuration will eliminate the need for temporary support and bracing during the erection.

- special fixtures should be built into the components and the receiving structure which will facilitate their grasping, orientation, positioning and connecting.

- connecting between components should be made as simple as possible.

- finishes should be selected, whenever possible, from the group most amenable to robotics, namely the group which involves finishing of continuous surfaces.

- finishing should be made as homogeneous as possible, i.e. of such technological content that no task will require multiple robot activities for its execution. If a task requires two activities (e.g. spreading and smoothing), they should be technologically designed in such a way that a robot will be able to execute them in immediate succession (or at least from the same station) with two effectors mounted on the same arm.

- there should be an easy access for robot manipulators to all work locations.

4 THE COMPUTER AS PART OF CONSTRUCTION ROBOTICS

In addition to being an integral part of a construction robot, the computer offers great potential for improved productivity, quality and, indeed, capability on the construction site. These advantages also apply to other areas of application in unstructured environments. The techniques of computer aided design and manufacturing are ideally suited to construction. In addition, the use of artificial intelligence in knowledge based expert systems offers the potential for a greatly expanded capability in topics ranging from initial deisgn to emergency maintenance response.

4.1 CAD-CAM

The full potential of robotized construction requires that planning, design, construction, utilization and evaluation be completely integrated. This process can be most effective within the framework of a closed system having authority over the design, prefabrication, primary construction and management of the project. Such an integrated system is facilitated by computer-aided design and manufacturing procedures.

Future CAD-CAM building systems will evolve around a group of standard prefabricated components - exterior walls, floor slabs, sanitary units, stairs, etc., each one including elements of structure, carpentry, electrical conduits, finishing, temporary support, jointing to other elements, and various inserts and fixtures as needed. The components will be carefully designed in view of the performance requirements of the building type for which they will be used, and the features of the robots which will be employed for their assembling and finishing. Planning for robotization will include types of robots, their tasks, work stations, movement pattern, critical points, transfers and location of materials.

A further step in this direction being proposed by several building innovators [48] will be preparation of a comprehensive "library" of components, of alternative shapes and dimensions, which could be used for erection of buildings of different sizes and layouts. The design of a particular building will then consist mostly of the selection of a layout which can be constructed with the library components. This form of construction will be just as individual or customized as conventional buildings. CAD-CAM building systems such as these are currently being used for house construction in Japan with cost savings estimated to be at least 20%.

Using CAD-CAM based building programs, all of the following processes can be linked in one database which is both general, in that it applies to all buildings constructed from that system, and unique for each individual structure.

- specification of needs by customer
- preliminary layout and design
- final design
- cost estimates of the building, its components and finishing
- lists of materials for the various components and their finishing on site
- schedules for the various activities on site
- production plans for the components in the prefabrication plant
- distribution of work drawings and specifications to all construction/production teams in the factory and on the building site
- packaging and dispatching plans for transportation of components from the factory to the site
- programs of robotization on site in terms of robots to be used, work areas, work stations, supply materials, transfer points, etc., as explained before
- progress and cost control reports for work on site and in the prefabrication plant

- payments, billings, and accounting associated with the production in plant and the construction on site.

The system may be further extended to update or change a design through the following functions:

- producing a computerized alternative to any layout or design. The alternative will be as close as possible to the desired layout and will be constructable with the available library elements.

- customization of the available components by allowing adjustment in the basic (library) components in terms of exterior dimensions location of windows and doors, electrical outlets, exterior finish, etc. The system will respond to the desired changes, within allowable limits, by adjusting the design, and all the other outputs (cost, shedule, etc.) derived from it.

- automatic adjustment of molds and other production facilities in the plant to the customized design of the various elements.

4.2 Expert Systems

Knowledge based expert systems are computer programs using internal decision structures different from conventional algorithmic programs. The principal elements of a knowledge based expert system are a *specific knowledge base* incorporating the expertise of one or more individuals. The knowledge base is restricted to a particular domain such as preliminary structural design or techniques for interpreting sensor data and images. The control program or *inference machine* may be common to many expert systems but for particular applications it acts with the specific knowledge base to produce answers. The data or *context* tailors the knowledge based expert system to an individual problem as for any computer program. Artificial intelligence may be used in an expert system, particularly in structuring the inference machine.

Knowledge based expert systems have great potential for use in construction and other problems involving an unstructured environment. Fenves and Rehak [8] have defined this potential to exist at three levels within the construction process:

- as integral components of construction robots, providing components of the robot's sensing, planning and control functions.

- as support functions to construction robots in the areas of interpretation of site conditions and evaluation of completed tasks.

- as part of an integrated design process which explicitly takes into account the capabilities and constraints of construction robots.

These three levels include essentially all of construction and provide for an almost limitless range of future applications. In fact, knowledge based expert systems may prove to be the key which allows for the practical extension of robotics into unstructured typed of problems and environments.

Few applications of knowledge based expert systems to construction problems have been reported. Among the initial efforts in this direction are:

- a failure and operation diagnostician for automatic transit systems called MOVER [7]
- strategic and tactical control of an automated tunnel boring machine [38]
- diagnosis of machine faults [7],[38]
- interpretation of sensor data for locating reinforcement in concrete [27]
- interpretation of multisensor data used for subsurface mapping of excavation targets [32]
- automatic interpretation of cone penetrometer data [28]
- preliminary structural design [22]

5 CONCLUSIONS

Applications of robots to problems of unstructured environments, including construction, can be justified for several principal reasons. Work in hazardous environments and an extension of normal human capability have been the motivations for most development up to this time but the economic problems of lower productivity in construction are an incentive for use of robotics.

The potential for using robots in construction applies both to improving the quality and efficiency of existing construction and also as a basis for developing entirely new forms of construction. A comprehensive study of the impact of robotics on building construction has been concluded. As a basis for considering the impact of robotic technology, the building process has been broken down into a limited number of basic activities. These activities can be done by four classes of construction robots. Using these robots, the complete process of constructing buildings can be redefined. This new building process offers the potential for increased quality and lower cost.

The computer offers the basis for widespread and fundamental changes in construction as well as similar areas such as agriculture, mining, undersea and space. CAD-CAM and knowledge based expert systems are developing rapidly and have the potential for applications in all facets of the unstructured environment. These applications will develop before robots are extensively used in construction.

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