# Application of Robotics to Building Construction

by

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## 1 Statement of the Problem

Employment of robots for performance of various production tasks is gaining an ever growing application in the manufacturing industries. The number of robots employed in the US industry grew according to [R2] from 200 in 1970 to 5,000 in 1981. It is estimated by the American Robot Association that the number of robots in the US will reach 15,000 in 1985, and 100,000 in 1990.

The growing employment of robots is accompanied by a considerable research and development effort in this area. According to [R10], research in robotics is carried out at the present in 20-25 academic research centers and government scientific laboratories, and a similar number of commercial enterprises. The volume of government sponsored research in robotics in the U.S. was about 20 million dollars in 1982. The investment in research of the private sector was probably even larger.

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This trend has not been reflected in the construction industry. The number of robots employed in the US construction is nil at present. Almost no funds are invested in research and development for possible applications in the future.

The lack of active interest in robotization of the construction work is largely caused by the particular features of construction: the unique nature of every project, production moving from one location to another, divided authority over the process (between owner, designer and contractor), rugged environment and volatile market. These features have in fact always impeded the process of building industrialization. Traditional "working" solutions were usually preferred over new ideas borrowed from other industrial fields. Introduction of robots which represent a very high level of industrialization and require organizational and technological modifications of the existing processes has therefore never been seriously considered in the building enterprises.

Construction is however the single largest industry in the US economy. Its output accounts for about 8% of the Gross National Product. Its employees constitute about 6% of the total labor force and its workers - about 10% of the blue collar workers in the US. The private investment in construction accounts for 40% of the total private domestic investment. It is also one of the least efficient industries as evidenced by its productivity decline (1.5% annually over the last decade), low output per worker (lower by 40% than the industrial average), and slow technological change. Construction work is strenuous and often performed under harsh and hazardous conditions. This is reflected in high wages (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, 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 environment deserves under such circumstances serious consideration.

## 2 Objectives of the Study

In view of the problem described above, the objectives of this study were defined as follows:

- To identify possible applications of robotics to the various building construction tasks,
- To specify robot requirements necessary for performance of these tasks,
- To examine the general feasibility of robotic application at the present and future state of building and robotic technology,
- To outline a procedure for detailed planning and evaluation of robotic application to performance of the desired activities.

## 3 Method of the Study

The study [1] consisted of the following stages:

1. Survey of existing knowledge with reference to the system explored . The survey comprised the following sources:
   a. Books, papers, symposium proceedings, trade periodicals in the field of robotics.
   b. Books, manuals, specifications and other publications on construction technology.
   c. Communications with experts in the field of robotics (Carnegie-Mellon, SRI, Charles Draper Laboratory).
   d. Communications with robots manufacturers, major construction firms, distributors of construction equipment.

   These sources are enumerated in Chapter 8 of [1]. The references to their findings are included in the text.

2. Examination of the present state of robot technology in view of building construction needs (described in Chapter 2 of the study).

3. Examination of the building construction methods in view of the robotic performance capacity (described in Chapter 3).

4. Specification of robot requirements with reference to major types of construction activities (Chapter 4).

5. Examination of robots implementation needs in building construction (Chapter 5).

6. Economic evaluation of robots applications to building construction (Chapter 6).

Conclusions and recommendations (Chapter 7).

## 4 Conclusions

The findings of the study can be summarized as follows:

a. Construction is the largest single industry in the United States, both in terms of its output, and the labor force employed in its projects. It is also one of the least advanced, in terms of technological progress and productivity. The largest and the most homogeneous part of the construction output are the buildings which account for 70% of its total value. Any technological innovation which could increase the building construction productivity would therefore have a highly beneficial impact both on the national economy and the welfare of an individual consumer. As such it should be thoroughly examined and encouraged.

b. The robotization is gaining an increasing acceptance in the manufacturing industry. The robot population in the U.S. is growing at an exponential rate and is expected to reach, towards the beginning of the next decade, 100,000 units. This growth is accompanied by a large investment in research and development of the robotic technology. No parallel trend is evident in the construction sector. No robots are employed in construction at present and there is almost no research and development towards this end.

c. The robotization of the construction process is more difficult than that of the manufacturing production, due to dispersion of the construction activities over many sites, distinctive nature of each project, changing work location within the project and the rugged conditions on the building sites. Despite these conditions many building construction activities can be robotized at the present stage of technology with promising economic results given an appropriate design of the robotic equipment and a suitable organization of the construction tasks.

d. The main components of a robotic system which should be examined with reference to application in the building construction industry are the manipulator, the effector, the control unit, the sensors, and the locomotion mechanism. Almost all building activities, except for hauling of large structural members, can be performed with the existing configurations of *robot manipulators*, which must, however, be made sturdier considering the ruggedness of the building environment. The handling of heavy members can be performed with existing crane like manipulators. *The effectors* needed for building construction can be classified into two categories: grippers adapted to the nature of the objects to be handled, and specific working tools depending on the task to be performed. The *robotic control* of building operations has two levels. At the first level it ensures through appropriate preprogramming the performance of a required task (like painting, welding, etc.) at a static location. At a higher level it directs the movement of the robot over the entire work area with an aid of feedback from sensors and appropriate artificial intelligence algorithms. This second level requires, at the present state of technology, an additional development effort for dependable and economically feasible robot's navigation. The control of robot operations can be facilitated by human intervention, either direct, or through a teleoperator. *The sensors* needed for ensuring required quality of preprogrammed activity at the two control levels belong to the vision, contact and proximity classes. All these sensors require additional development for dependence, sturdiness and adaptation to building conditions for feasible application at the second level of control, and even for many operations at the first level. The *mobility* of robots over continuous surfaces does not pose any mechanical difficulty and depends entirely on the development of sensors and control units. Human intervention will be required when the robot is to move over discontinuous surfaces like, e.g. from one to another floor in the same building.

e. The building construction activities consist of handling of building components, connecting them to the existing structure and finishing them by application of appropriate mechanical treatment. The most amenable to robotization are the activities which require covering (with liquid or semiliquid substances) or conditioning of large continuous surfaces - vertical or horizontal, e.g. painting, spraying, plastering, trowelling, etc. These activities can be robotized without difficulty at the present stage of technology. Less amenable, but possible to robotize are activities which require moving the effector at different locations in a predetermined pattern - linear or point to point, e.g. welding, bolting, jointing, spreading of fabric rolls, etc. These activities can be robotized in building with a proper adaptation of sensory devices. The least amenable to robotization are activities requiring handling and assembly of components like structural steel members, precast elements, bricks, formwork, sheathing, etc., which require picking, orientation, precise positioning and often temporary supporting of objects.

f. A selective robotization of the building construction works can be attained with minimum development if applied to the first two groups of building activities as enumerated above. A more comprehensive robotization particularly promising under hazardous or harsh environments must, however, involve also assembling tasks. The process can be simplified when using large self-supporting prefabricated components comprising as many building works as possible, and thus minimizing the extent of assembling work on site. The finishing work on site should be limited, as much as possible, to simple, one activity, covering or conditioning tasks.

g. Four types of robots can perform all major building construction tasks. *The first type* used for handling of large building components may have a configuration of a building crane or a concrete pump boom. It will use grippers for picking and placing of the components, and a control unit with teleoperated or sensory guidance. *The second type* can be employed for most of interior finishing, and connecting works. It will use an antropomorphic arm with a reach of 3-4$^{m}$ and tools according to the type of work to be done. It will operate from static work stations, each one encompassing a room size service area, with a preprogrammed mode of operation. The quality and precision of its work can be monitored by vision, tactile or proximity sensors. The robot may be used either directly by a working crew who will move it from one work station to the next and set it up for operation at each work station, *or* guided by a teleoperator, *or* act autonomously with movement between work stations and its setting up for operation at them monitored by sensors and an appropriate artificial intelligence algorithm. *The third type* employed for finishing of large horizontal surfaces will consist of a self-propelled carriage with the finishing effector mounted underneath. It can also use one of control alternatives, and associated sensory devices as described above. The *fourth type* will be employed for finishing of vertical exterior walls. It will employ a carriage suspended from the roof's parapet with the effecting tool mounted between it and the wall surface.

h. Actual robotization of the building tasks must be preceded by a detailed predevelopment design process which includes analysis of the present construction method, designing several alternatives of robot employment, selecting of conceptual design of system components for each alternative, preparation of appropriate operational procedure for each alternative, and conducting a thorough feasibility study to determine the optimal choice, which will be consequently detailed for development.

i. The development effort will focus on a manipulator with sufficient reach (for the general purpose robot), and a carriage adapted to movement between work stations. Both should be made sturdy enough to operate in rugged building environment but their weight should be reduced as much as possible so as not to impose excessive loads on the structure. The development will include also effectors with their feeding systems for performance of different construction tasks, and sensors for interaction with guiding devices fixed in the structure.

j. The robotization of building construction may be easier within the framework of *closed systems* using large selections of predesigned components to be prefabricated in plant, and assembled on site. Such systems may employ CAD/CAM programs and procedures for design, managerial planning and robotization - on site and in prefabrication plant, of building projects, for optimal utilization of human, robotic and material resources. An extension of such systems will allow for automated adaptation of existing designs to particular requests of users. It will also allow for automatic adaptation of production resources in the prefabrication factory to the changes in the basic design.

k. A preliminary economic analysis indicates that a value of a construction robot to its user may be, under normal working conditions, approximately $250,000, based on 1983 prices. The value was calculated as the present worth of savings in labor from robot's employment less the associated operation and maintenance costs. It is expected, based on the current cost of manufacturing robots, that this value will exceed the cost of purchasing and installation of a construction robot after its development. This expectation assumes rational utilization of the robots in suitable building projects. Should the robots be used at a rate much lower than the indicated above, or in building projects very ill structured for robotization, they will have difficulty competing economically with the conventional building methods.

l. The value of robots in building construction increases under conditions which impair the performance (and decrease the productivity) of human labor. Such conditions arise when the building is performed under harsh weather (very hot or very cold), in high altitudes, or in extended periods of overtime work. The economic analysis indicates that the value of robots under such conditions may be higher to the user by 50% and more than under normal conditions, as discussed before. The value of robots is particularly high when their use can limit human participation in hazardous tasks with a high fatality or injury incidence to workers.

m. Another important benefit expected from robots application is the improved quality of the product due to a higher accuracy and a better control of robot operations. The benefits include savings in materials, in repair work during the construction, in maintenance thereafter, and a higher satisfaction of the user. These benefits are difficult to quantify, however their value is considered by users as important as productivity gains attained with robotization.

n. The economic success of robotization in building will ultimately depend upon the extent of replacement of the human labor. It may also change the contents of many existing tasks. Such changes may be resisted by the workers on site and their unions. The robotization will certainly require changes in the contents of managerial tasks on and off the building site, and the training necessary for their performance. It may also be resisted by the management, especially at the lower levels, in the construction companies. The resistance of labor and management may be avoided or at least mitigated if the implementation will be preceded by a planned effort to secure the cooperation of all parties.

## 5 Recommendations

The conclusions of this study indicate that robotization of the building activities, if pursued with a rational and selective approach, may result in considerable productivity gains to the construction industry. The development of appropriate methods, equipment and procedures toward this end must be preceded, to succeed, by a thorough planning effort, not related to a particular project but with a general purpose common to the whole building sector. The planning should focus on the following subjects:

a. Design of the robotization process for different groups of building activities. The design will be aimed at arriving at the optimal robotic systems and their employment procedures for each group of activities. The groups may be centered around the four different types of robots as suggested in this study, namely:

   - handling and positioning of large elements
   - interior finishing and connecting activities
   - finishing of large horizontal surfaces
   - finishing of exterior walls.

   The design should indicate the optimal robotic system (in terms of manipulator, effectors, control unit, sensors and mobility) for performance, the optimal procedure (or alternative procedures) for its operation, and define the conditions for the feasibility of its application.

b. Design of a comprehensive robotization of the total building process with minimum human intervention, with specific potential application under ambient conditions which preclude the use of conventional building methods. The design should indicate the recommended building technology to be employed for all construction tasks, the optimal robotic system or systems, and the organizational procedures for their employment.

c. Conceptual design of a CAD/CAM system for design, production and management of robotized construction work. The system will receive as an input preliminary design of a building and will produce design drawings of building components, specifications for their finishing on site, cost estimates of components and site work, production schedules in prefabrication plants, schedules for components shipping from the plant to the construction site, erection schedules and robotization programs on site. The robotization program will indicate the number and designation of robots employed, their work stations and tasks, and their mode of transfer between the work stations.

d. Conceptual planning of a robotization of work in prefabrication plants for large building components - exterior walls, floors, partitions, etc. The plan should indicate the robotic system, optimal production organization, and desired modifications in the existing production technology which will allow most feasible prefabrication at minimum human intervention and maximum adaptibility to architectural design requirements.

e. Analysis of the social implications of the robotization in building construction. The study should indicate, based on a survey of labor and management opinions, a strategy which may gain most cooperation and least resistance from all parties involved in an implementation of robotics in building construction.

## 6. References

1.Warszawski, A "Robotics in Building Construction"
Technical Report R-84-147 Department of Civil Engineering,
Carnegie-Mellon University, Pittsburgh, PA 1984