ISSUES IN THE DEVELOPMENT OF A BUILDING ROBOT

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ABSTRACT

An overall automation of construction process is expected to significantly improve the efficiency and quality of building. An automated construction consists in fabricating of components off site and their robotized erection and finishing on site. A development process of an interior finishing robot includes an analysis of an optimal configuration for this purpose, physical testing of its various activities, adaptation of building works to robot capacity, and a careful planning of its employment routine.

1. Introduction

An extensive automation of the building process - the design and the construction - is an overall goal of a research and development effort going on in many countries. It is expected to improve, with an aid of the new automation/information technologies, the productivity of building and the quality of its product. The principles of the future automated building system could be summarized as follows:

a. The design is to be performed with an aid of interactive 3D computer graphics model, accessible to all parties participating in the design process.
b. The design is to use a data bank of standards, algorithms, codes, tables and typical details which could be of assistance in its course.
c. The design is to be helped by a knowledge-based expert system or systems, guiding the user towards an efficient application of the various pertinent rules, and the utilization of the various types of information from the knowledge base.
d. The construction is to employ as many as possible factory-made components - beams, columns, walls, floor slabs, stairs and others, which could be produced with well defined methods, and with especially adapted resources.
e. The production of these components is to be automatically planned and controlled with an aid of design information transferred to the plants with the building orders.
f. The erection, jointing and finishing on site of these building components should be accomplished with automatic/robotic devices. The employment of these devices should be very carefully planned.
g. The existing building technology should be adapted to the special needs of automation.
h. The total process should be controlled, documented, and administered with an aid of a computerized information system.

The system, as described above, can be viewed as an ultimate goal and its attainment can be divided into individual tasks. Those tasks should be related in their general principles, but independent in their development and application.

The automation on the building site, which is the subject of this paper, should be viewed in this context. It should be planned and developed within the general scope of building automation, but in such manner that it could be applied independently, and contribute on its own merit, to the efficiency and quality of the building process. The problems of robotization on the building site were reviewed and analyzed in [4]. In the context discussed here, the automation on the building site could be employed in these processes: in the erection of the prefabricated elements, and in their subsequent jointing, finishing and complementing. The handling of components with a crane is very much automated even today. It can be enhanced by an automatic control over crane movements, and automatic attachment and disattachment to a crane of the handled components. The distinctive benefits of even partial automation of these functions will be discussed elsewhere.

The other functions on site, to be automated, involve the various works to be done in the building after the erection of prefabricated components. These works often constitute a serious bottleneck which hampers a fluent execution of the building process. Their possible performance by a robot raises various questions, which have to be addressed before proceeding with the development work. The complementary works involve the exterior and interior finishing of the building. The former has been addressed in various prototypes described in [2] and other sources. The latter will be a subject of this paper.

2. The issues in the development of the interior finishing robot

There are several important questions which must be addressed before the actual development of a building robot. These questions will be reviewed here, and some tentative answers to them will be offered. A development program, described later, is based on the assumptions derived from them. Different assumptions will necessarily lead to different avenues of research.

First, should the main complementary works on site be performed by one multipurpose robot or by a series of robots, each specializing in a particular task? A specialization oriented development, i.e. a robot designed independently for such tasks as painting, jointing, building, etc., will almost certainly result in a higher efficiency with respect to payload, reach, number of degrees of freedom, etc. On the other hand, to be justified economically, a robot for each particular task must be continuously employed, because otherwise it will not be justified economically. Since the complementary building works would be performed in similar enclosed spaces, their different content will mainly involve the effector and its materials feeding system. A common configuration of arm, locomotion and control systems seems, therefore, justified under such circumstances.

Second, what will be the nature of the robotized work. Unlike the industrialized production which is structured around a static work station, the construction is distinguished by its continuously changing work location. Consequently, a construction robot may need to move with the work progress, as does the construction worker. Alternatively, it may work from a limited number of work stations, and in such case it can operate in a fashion closer to a regular industrial robot. The eventual decision between those options depends on the nature of the task performed. Tasks with a very small work content, at any given location, will probably require a configuration adapted to a continuous movement during the work performance with a strong emphasis on the movement control system. Tasks with a larger work content at a location can be performed from static work stations, very much as in the industrial work.

The third question has to do with the configuration, the reach of the robot, and the payload it will handle. Most of the construction tasks in regular buildings are dispersed over a three-dimensional space, i.e. a room or a hall for residential, commercial, or public purposes. The dimensions of the robot will be determined by such three-dimensional space it has to serve from a single work station. The vertical dimension of interior space in residential and most commercial buildings, is between 2.70-3.00m. The most common interior enclosed space in residences, offices, hotels, etc., has about 10-14m^2 area. The length of arm required for performance of tasks on the periphery of such space is between 2.50-3.00m, depending whether the work is performed from one or more work stations. The required payload depends on the weight of building components (blocks, bricks) or tools, handled by the robot. It seems that most of these components and tools can be so restructured that the payload will not exceed 10 kgf.

A related question is whether to select one of the available industrial robots with a desired work envelope, or develop a special purpose robot for the performance of the selected tasks. It appears that it is almost impossible to find an industrial robot which will conform to the various limitations imposed by the regular building environment. The weight of the robot cannot exceed 400-500 kg if the building floor is not to be especially reinforced for the robotic work. In contrast to the "nominal" work envelope, as indicated for the industrial robot, it is necessary to evaluate the robot's performance in view of the "task-oriented" work envelope - which allows to reach each point at a desired orientation, and a "space oriented envelope" which defines the points the robot can reach, without colliding with the space enclosure or other obstacles.

The next question has to do with the autonomy of the robot. At one extreme there is a robot which can complete "a day's work" or a considerable section of work without any human intervention. Such a robot must be able to autonomously navigate between work stations, to locate itself at a precise point at a work station, identify the work to be done, and its starting point. For these ends it must possess a very extensive sensing capacity and a very powerful control mechanism. On the other end, there is a robot which is employed by a working team, as an extended work tool. Such tool will relieve the worker from the majority of his physical tasks, but will leave him in charge of all control and planning functions of the robot.

It seems that a reasonable intermediate solution would be to view the robot as an autonomous work station, once it has been established, precisely at its work location. Consequently, it would be moved from one work station to the next by a human operator who also determines its location, and places the robot at the initiation point of its work. From this point the robot performs its whole task at the work station, in a fashion preprogrammed for each particular building or its part.

A closely related issue has to do with the scope of the robotic performance. The robot may be designed to perform all of the work in any prescribed task even in small and ill-structured spaces such as bathrooms, toilets, corridors, etc. This will require a development of extremely agile, sophisticated and costly robot. Or, the robot could be used only in building with large and regular spaces which allow an easy access to all locations for a robot with a conventional configuration. Alternatively, some especially "unfriendly" corners and edges could be left over to human completion? This would allow the use of a simpler and a less expensive robot, and also increase the population of candidate buildings for robotized work. The choice of the latter possibility depends, of course, on the amount of work left over for the human completion. Only if this amount will be insignificant, it will be feasible to employ robots in the finishing works. It would be worthwhile, therefore, to develop some criteria for adaptibility of a building for the robotic work, so that a decision can be taken in advance with respect to any particular candidate building under consideration.

The principles outlined here formed the basis for the development program of a building robot at the Building Research Station of the Technion.

3. The research program

The research program at the Building Research Station of the Technion, tries to solve the various problems which were outlined in the former section. The program consists of the following objectives:

a. To determine the optimal configuration of the interior finishing robot.

b. To physically test the performance of the various tasks by the robot and its interaction with the environment.
c. To restructure the basic construction tasks in such manner that they will be amenable to robotic execution.
d. To develop a procedure for planning of the robotic work.
e. To examine methods of education and training of the construction personnel for the performance in the automated environment.

The research program for the attainment of these objectives will be now very briefly described.

An Optimal configuration of the construction robot

As was noted before, the configuration of the interior finishing robot requires a special study with regard to the following decision variables:

a. The configuration of the arm - the geometry of joints and links.
b. The payload and its effect on the structure (and cost) of the arm.
c. The capacity of various actuators at the joints, and their effect on the productivity and the cost of the robot.
d. The configuration of the carriage.

The constraints of the planning process were outlined in the former section. Basically, the robot must:

a. Reach, from a static work station, all specified locations in a predefined space, at a required orientation of the effector.
b. Handle the building components and the work tools.
c. Move into and from the defined work spaces.
d. Conform to the live load requirements as specified for the particular building.

The decision variables pertaining to the configuration and the capacity of the robot were examined within a range of their possible values on a model layout consisting of several typical spaces, with an aid of a computer graphic program ROBCAD. The program simulates the various physical aspects of the robot's performance. An optimal value for each variable (link, joint, actuator, carriage) was determined in view of these criteria:

- The productivity of the robot, i.e. the number of workers the robot can replace.
- The maneuverability of the robot, its adaptibility to various types of building layouts.

Those two were obtained from the simulation model and the cost of the robot - its investment and operating expenses, which were calculated separately for each alternative.

The work on this subject was described in [6], and has been advanced further since then. A picture of the simulation procedure is shown in fig. 1

The physical performance

The physical performance of the various tasks by the robot, and its interaction with the environment, can be explored simultaneously with the configuration analysis. The purpose of this study is to test the various working tools and their operation, the handling problems of the various building components, the performance of sensors, the overall control mechanism and the various algorithms employed for this purpose. The performance of the various tasks can be explored with an aid of a regular industrial robot, which can manipulate its arm, in a broad sense, in a similar way to the future construction robot. It is also desired that the robot will have some movement capacity (e.g. by having its base mounted on rails or wheels) so that problems associated with the robot transfer from one station to another, could be examined.

The study can even be performed, at least at the initial stage, with an aid of a small educational robot, to the extent that such robot will possess the necessary manipulation movement and control capacity. The results of the experiments will then apply to the simulated tools and building components.

The experiments in this area, at the Building Research Station of the Technion, are being performed in two stages. The first stage employed a small educational robot with a reach of 610mm, 5 degrees of freedom and a lifting capacity of 1 kg. The experiment included 3 types of tasks - building of "dry" block partition, painting of interior walls, and sealing of joints between the building components. These three types of tasks represented the main groups of operations which are customarily performed by a robot: handling/orientation of objects, processing of two-dimensional surfaces and execution of linear work patterns. Special tools were designed for each of these activities. The robot had some movement capacity by being mounted on a servo-driven carriage. It could interact with the environment with an aid of two types of sensors - one reacting to light reflected from a fixture built in a wall, and the other - reacting to contrasts between areas with different types of illumination. The first one was used for identification of the various initiation points, and the other for identification of obstacles in the work path.

The use of a small scale robot had some very important limitations: the limited payload did not enable a development of good and reliable work tools; the effective work envelope was too small to simulate the actual geometry of the work space; the results of the experiments pertained only to "scaled" tools and components, and were true only to the extent that these could realistically represent the real life items. This subject has been dealt with in [3]. A picture of the system is shown in fig. 2.

To overcome these limitations, the second stage of experiments was to employ a full size industrial robot with a reach of 1.250-1.500mm - a payload of 10 kg, and six degrees of freedom. The "seventh degree of freedom" was to be attained by mounting the robot on a carriage driven by servo motor.

The difference between the reach and the configuration of the test robot, and the planned construction robot, results in a reduced maneuverability and the work envelope of the former. The use of such robot allows, however, for a full scale representation of all building components and building tools, and their mode of operation and control.

<u>The planning of robotized work</u>

It was explained before that the most important element in the economic feasibility of the construction robot will be the extent of its utilization. As pointed out in [5], a construction robot must be utilized at least at 50-70% of its full capacity, to be justified economically. It was also pointed out before, that in order to extend its application range a robot might be employed in buildings which, by their configuration, do not justify a full robotization and require that some complements will be done by manual work. It is therefore necessary, for a given layout of a building, to find out what part of the work could be robotized, and to what extent the robot could be utilized in the process. Consequently, a tentative work plan, or work plans, must be prepared for the robot, which will enable the calculation of these parameters. These plans will indicate:

- the location of work stations.
- the work performed from each work station (and the work left over for human completion).
- the progress path from one work station to the next.

The algorithm employed for this purpose, at the Building Research Station, used the concept of an effective work envelope, i.e. a work envelope which ensures access of the effector at a required orientation and unobstructed movement of the arm for this purpose. The projection of this envelope indicates the work area which could have been effectively covered by the robot. The manipulation of such projection along various paths, varying the locations of work stations, could reveal the most efficient way of performing the task, considering the time expended, the extent of employment of the robot, and the work left over for human complementation. Ultimately, the employment of the algorithm, for various types of buildings, would yield some general rules as to the applicability or inapplicability of the various types of layouts of residential buildings, offices, etc., to the robotic work, based on the accepted criteria of cost and utilization. An output with location of work stations is shown in fig. 3.

Restructuring of the basic construction tasks

As was explained in the beginning, the purpose of the interior finishing robot is to do the jointing, finishing, and other complemntary work which remains after construction of the exterior prefabricated shell. In more specific terms, the following tasks were identified as receiving the highest priority for the robotic performance:

- support of the shell (structural and envelope) components when placed by a robot.
- structural connection of the various shell elements.
- building of vertical space dividers (partitions, walls).
- coating of walls and ceilings.
- covering of floors.
- sealing of joints between horizontal and vertical space dividers.
- attaching various conduits (for installation and electricity) to walls and ceilings.
- attaching various fixtures to walls and ceilings.

The first two tasks have to do with the shell-erecting robot which is discussed in a separate paper.

The building of partitions had to conform to the following constraints:

- The building blocks had to be of such size as to allow a flexible shaping of partitions according to the architectural design.
- They had to be made of such material that their weight would not exceed the robot's payload.
- The building was to use a dry connection of the blocks, so as not to require repetitive adaptation of the effector during the construction process.

The method tested at the Building Research Station for this purpose, included lightweight concrete interlocking blocks, which were to be subsequently stabilized by injection of concrete or by application of fiber reinforced coating. A picture of such wall is shown in fig. 4.

The walls, partitions ceilings had to be coated with a single layer of sprayed substance which was to yield a finish of a required thickness (5mm), texture and color.

The floor had to be covered by a self-levelling substance which, when spread by a robotic operation, could render a floor surface of a desired thickness and aesthetic appearance.

The sealing of joints between space dividers; it has been planned, for the facility of robotized construction, that all the space dividing members would not exactly adjoin to their neighboring components (e.g. partitions to walls, partitions to top slab, etc.), as is customarily done in conventional building, and a certain space - 5-30mm will be left between them. This space was to be filled by a robot with an elastomeric substance which would satisfactorily adapt itself to the geometry of the joint between the two components, and would satisfactorily perform (with regard to aesthetics and function) afterwards.

Self-supporting fixtures built into the shell components were planned to stabilize and support them at their desired location and orientation without human aid once they are placed there by the handling robot or by a regular crane.

Structural connection between precast shell components had to replace the existing bolting or welding connections which are ill-suited for the robotic execution. The proposed alternative is using adhesives which have the necessary attributes of structural performance and can be applied, by a robot, to the connected parts, with an ordinary sealing gun.

Attaching of conduits and fixtures to walls had to be also robotized. Installation of electrical conduits, and their various fixtures in the building interior, is an ill-structured work which is performed, at present, by skilled manual workers. Robotization of the installation work requires restructuring of these items, so that they could be easily stored, picked and manipulated by the robot, and easily attached to the surface of building components.

A preliminary survey of methods applicable to these tasks was included in [1], and the work since then has been carried further.

Education and training of personnel

The ultimate success of robotization in the building site will depend upon its acceptance and understanding by the involved personnel. The education towards this purpose should be performed on two levels: the lower level of operators and maintenance personnel, and the higher level of site engineers and project managers. The training on the lower level will be directly involved with the specific technical and operational features of the construction robot. Such training should be undertaken, therefore, only after the completion of the development and the actual implementation of the robotized process. The education on the higher level must involve a general knowledge of robotics, and the various aspects of their employment on the building site. Such education should be included in the regular curricula of engineering schools. Building robotics is being taught now at the Technion - I.I.T., within the scope of an advanced computer methods course. The teaching includes a basic knowledge of general robotics - the configuration and performance of the prevailing industrial robots, their effectors, sensors and control systems. It also includes a general review of building robotics, and of the building robot prototypes developed. Two types of building assignments have been included in the program. One consisted of the planning of a whole robotic system for execution of a particular building task. The other consisted of structuring, programming and execution of an experiment with a small scale educational building robot.

4. Conclusions

The automation of the finishing works on site is, at present, a serious obstacle to the integrated automation of the building process. Employment of a robot which could perform most, or all of these tasks, must be preceded by a serious multidisciplinary development effort. Such development must include a thorough study of the following aspects of robotization:

- the tasks to be performed by the robot.
- the configuration of the robot.
- the mode of employment of the robot on site.
- the restructuring of the conventional building technology to conform to the robot's limitations and constraints.

- the education and training of people at the various levels of the building project operation and management.

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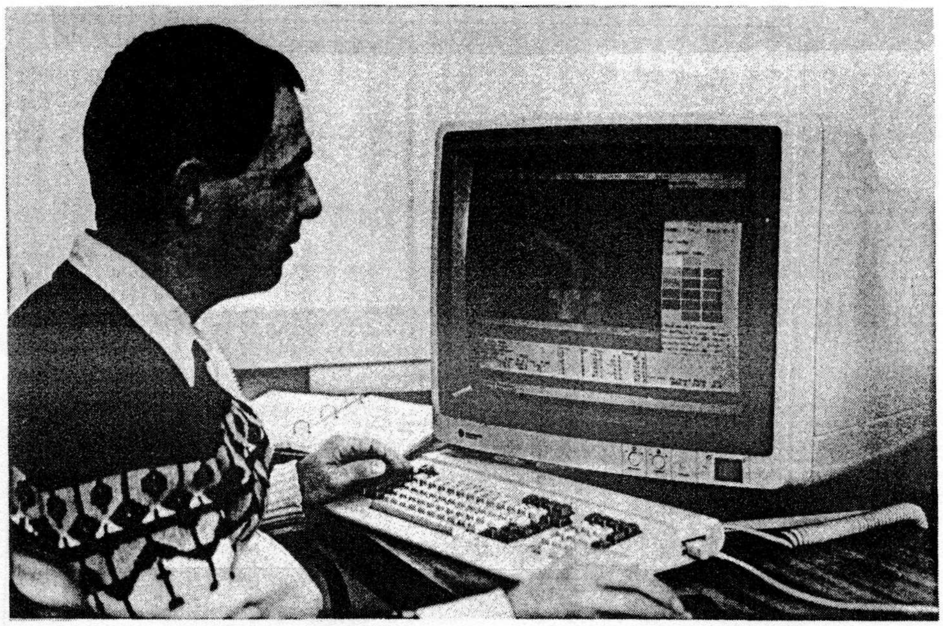

Fig. 1 - A work station for simulation of robot performance

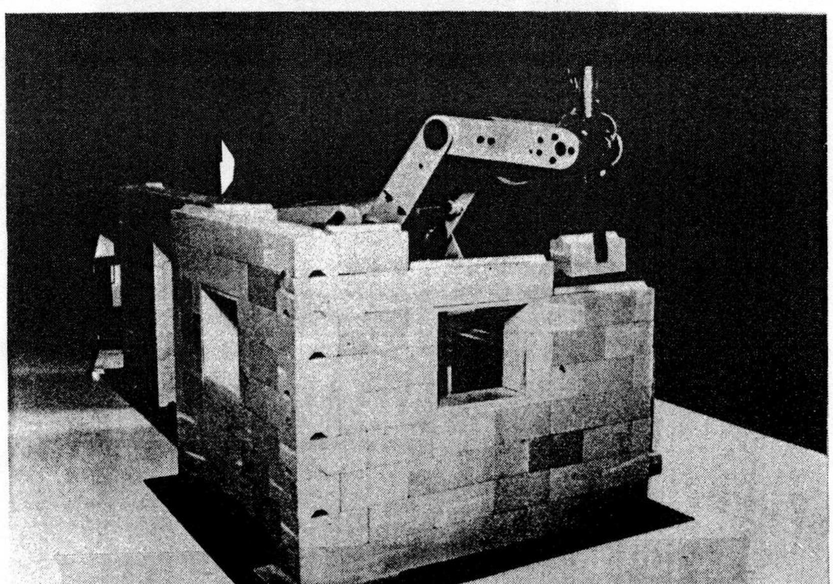

Fig. 2 - A model testing of construction robot activities

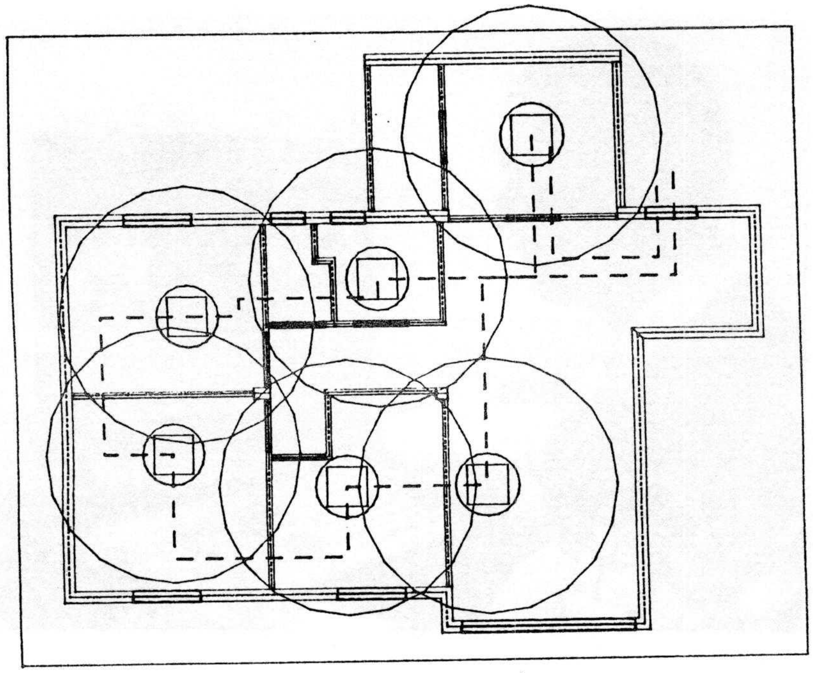

Fig. 3 - An output of robot employment planning program

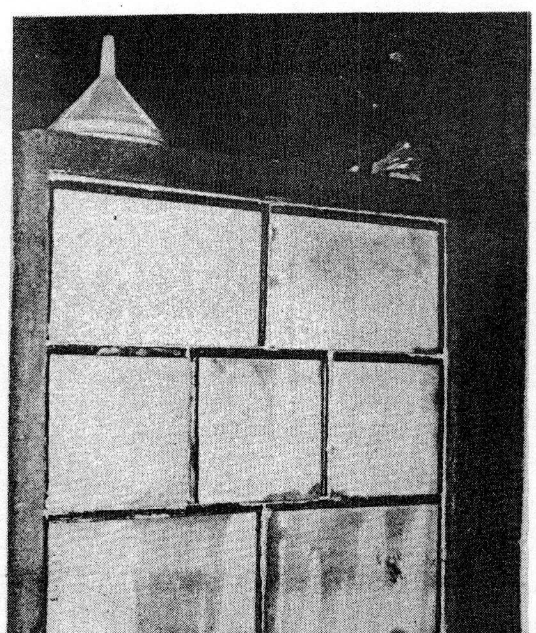

Fig. 4 - A dry wall building experiment