Implementation of Robotics in Building: Current Status and Future Prospects

By A. Warszawski,[1] Fellow, ASCE, and R. Navon,[2] Member, ASCE

Abstract: A survey to evaluate the state-of-the-art development and employment of building robots was conducted worldwide among construction companies, universities, and other research organizations. The methodology of the survey and its results are presented. The analysis of the results yields a gloomy picture of the present level of on-site of robot employment. The reasons for this situation are identified as follows: (1) Existing robots are not well adapted to building construction. (2) There are problems associated with the conventionally designed building. (3) It is difficult to justify robot employment economically. (4) There are managerial barriers. Consequently, recommendations are offered for more efficient future implementation.

INTRODUCTION

Construction automation and robotics have been generating much interest in the construction community over the last two decades. Early developments of one-site robotized concepts started to emerge, and even be tested, over 15 years ago.

The robots employed in construction have followed the same concept as those employed in manufacturing: Most of them use an effector (a gripper or a work tool) mounted on a multi-axial arm, and their tasks are defined and controlled by a computer. However, unlike most of the manufacturing robots, which perform preprogrammed tasks from static work stations, the construction robots have to be mobile and, when fully developed, will have to interact with the changing environment through sensors, adapting their tasks on the basis of the feedback received. Building robots have been employed in various tasks, including materials handling, various interior and exterior finishing tasks, and quality control, as enumerated later in this paper.

The configurations of construction robots which have been developed to date can be roughly divided into these main groups (Warszawski 1990):

- Exterior handling robots, which are employed in handling large loads such as concrete buckets, prefabricated elements, and steel bars, have a configuration similar to mobile cranes.
- Horizontal finishers, which are used for finishing (smoothing, trowelling, etc.) floor surfaces, have a work tool mounted on a horizontally moving carriage.
- Vertical finishers, which are used for finishing (e.g., painting) or inspecting exterior walls, have a work tool mounted on a vertically moving carriage.
- Interior finishers, which are used for various finishing and material handling tasks inside the building (painting, masonry, etc.), usually have an anthropomorphic configuration.

The purpose of the study underlying the present paper was to review the existing applications of building robotics and to assess their implementation in practice. The discussion is limited to building construction.

The high expectations of building robotics stemmed from the very serious problems the industry is facing: continuously declining productivity or, as stated by Whittaker (1986), "labor efficiency is alarmingly low in construction"; a high accident rate; low quality; insufficient control of the construction site; and the vanishing of a skilled workforce. The following paragraphs summarize some of these expectations.

A report describing cases in which robots were already performing economically useful tasks in the field for Japanese construction contractors ("Japan" 1983) gave rise to a feeling that construction robotics had become a reality. On this basis Paulson (1985), in a review and analysis of the emerging technologies, concluded that "perhaps, if no significant research effort evolves in the U.S., American contractors will be able to solve their problems by importing robotics and process-control machinery from overseas." Ueno et al. (1986), after being engaged in the development and on-site application of construction robots for over a decade, came to the conclusion that "the period in which construction robots are adopted as a curiosity is almost over in Japan."

Whittaker and Bandari (1986) were already looking at the next stage of construction robotics, in which a number of robots would work together. They reported that "robots were emerging in construction as a way to increase productivity, improve quality, and decrease hazards to human workers.... However, these industrial robot forms, though necessary, are not sufficient to achieve typical construction goals.... The requirement for multiple capability at the automated work site must be served by multiple cooperative robot agents."

Skibniewski and Russell (1989) say that "with less optimistic estimates for construction robotics due to their complex operational environments, it can be anticipated that their application can result in approximately 10–15% increase in overall construction productivity rate." In another paper, Skibniewski (1992) reported on early applications in the United States, saying that "the process of disseminating the early results from research and development of construction automation and robotics into industry practice is now slowly taking place.... A number of robotic prototypes have been designed and built in the U.S.; some of them have already found commercial application."

Researchers at the University of Texas at Austin have compiled a database to classify papers contained in the proceedings of several international symposia on automation and robotics in construction (ISARC) (Ochoa-Franco et al. 1994). In the first stage they collected data relating to ISARCs VII-X. Their analysis showed that the number of papers presenting conceptual systems had gone down from about 70% in 1990 to 45% or so in 1993. At the same time papers dealing with physical prototype systems were replacing those conceptually oriented, increasing from a little over 25% in 1990 to nearly 50% in 1993. The results of the analysis also indicate a clear trend toward an increasing number of papers on commercial sys-

[1]Prof., Dept. of Civ. Engrg., Technion, Nat. Build. Res. Inst., Technion City, 32000 Haifa, Israel. cvrabwa@tx.technion.ac.il.
[2]Sr. Lect., Dept. of Civ. Engrg., Technion, cvronie@tx.technion.ac.il.
Note. Discussion open until July 1, 1998. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 5, 1997. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 124, No. 1, January/February, 1998. ©ASCE, ISSN 0733-9364/98/0001-0031–0041/ $4.00 + $.50 per page. Paper No. 13450.

J. Constr. Eng. Manage., 1998, 124(1): 31-41

tems, which the researchers saw as solid evidence that construction automation was maturing and becoming a practical and attractive technology.

Less optimistic views have begun to be heard in the last two years. Poppy (1994) conducted a survey among 100 European specialists, on the basis of which he states that "overall automation and robotics in construction do not play a very important role in Western European countries.... The main activity is pursued by universities and research institutes, not by the industry or by construction machinery producers. The activity stems mainly from the availability of research money and is not driven by the needs of the industry.... In the past the major barrier to construction automation was lack of electronic components and systems. This is solved now, and the current obstacle is the high cost of automated systems, shortage of public money for R&D, and problems of acceptance." He reported on automation and robotics research and usage in Europe in 1994, which included: off-site production (concrete and asphalt mixing plants, production of standardized blocks and pipes, and initial developments in computer-aided manufacturing of large concrete units); masonry (prefabrication of masonry walls and a number of bricklaying machines); and control and monitoring of mobile construction machinery, which constantly inform the operator of the status of the machine; and renovation of old sewer pipes.

Other views from the United States are that "to date, few robotic applications are in actual field use" (Boles et al. 1995; Everett and Slocum 1994). Similar views come from Japan. Ueno (1994), who said in 1986 that construction robots would not be just a curiosity, now says that most of the construction robots will not be widely used because of their high cost and low performance. When robots are applied to one part of the construction process, the resulting productivity improvement is limited. He says that most of the single-task robots in Japan are teleoperated.

Another Japanese view is that "only a few construction robots have been made commercially available for the execution state of construction, because many of them are stalled at the demonstration stage" (Obayashi 1992). Furthermore, "most of the commercialized techniques replace hand work by machines, which means that they do not have the desired effect that could be achieved from high-tech systems" (Obayashi 1992). Obayashi identifies five problems leading to the low commercial use of construction robots in Japan:

1. Many developments are made for specific job sites and are not suitable for others.
2. There is no horizontal diffusion of knowledge between competing companies; therefore, each company has to invest all the development costs, making its development much less cost-effective.
3. No further development of initial systems is undertaken due to lack of feedback from different construction sites.
4. Robot manufacturers are aware of the evolving niche but are unwilling to enter this market.
5. Equipment-leasing companies are reluctant to add construction robots to their line of business due to lack of qualified technical supporting staff and the unsuitability of the existing systems to different construction sites.

It is important to know the real status of building robotics today to decide what future directions building robotics should take. The paper describes the findings of a survey conducted for this purpose and draws some general conclusions from them.

SURVEY

The general objective of the survey was to determine the scope of application of robotics in building construction. In more specific terms the objectives of the survey were:

1. To review the publications describing the development and implementation of robotic applications in building construction.
2. To determine the success of these applications, aided by a structured survey. For this purpose the exact status of the application was determined for each case.
3. To analyze the findings of the survey and draw conclusions regarding the extent of success of building robotics, and the reasons for success/failure.

The survey was limited to building robotics. It did not include various civil engineering applications (roads, tunneling, etc.). Nor did it include the employment of robots in manufacturing various building materials or components.

For the purpose of this study, a building robot was defined as an automated device employed to perform a building task on a construction site. This definition is synonymous with the one in the *Encyclopedia Britannica:* "automatically operated machines that replace human effort" ("Robot" 1997). Automation in a more general sense may be viewed as the capacity of a machine to execute a series of preprogrammed autonomous activities. It is usually, but not necessarily, associated with a closed loop feedback control of the performed activity, i.e., measurement, evaluation of results, and corrective action. This definition was considered wide enough to include all devices that are defined today as robots by their users or developers and are presented and discussed as such in the professional literature. Applying the definition used by the Robotic Industries Association (RIA, previously known as the Robot Institute of America)—"robot is a reprogrammable, multifunctional manipulator, designed to move material, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks"—may exclude many manually guided construction robots. The definition used by the Japanese Industrial Robot Association includes six levels of robots according to their extent of autonomy: (1) manual handling devices; (2) fixed-sequence devices; (3) variable-sequence robots; (4) playback robots; (5) numerically controlled robots; and (6) intelligent robots. This six-level definition is more appropriate in this respect, although one may argue that some types of mobile construction robots (used, for example, in floor trowelling) do not necessarily employ manipulators.

The survey covered the type of application, the characteristics of the robots (their configurations, control, and sensors), the stage of development/employment, and the reason for not continuing, if the development/employment was abandoned at some stage.

The survey involved all sources of information that were described in the following publications:

- Annual proceedings of ISARC (I-XII)
- *Journal of Automation in Construction* (volumes 1–3)
- IAARC's newsletters (1–12)
- Publications of robot developers
- Other trade and academic publications

The survey was conducted in two stages. The first included a structured questionnaire (Appendix I), the results of which were analyzed and presented by Warszawski (1995) and Warszawski and Navon (1996). In the second stage the resulting data was put in a standard format (Appendix II) and sent back to the survey participants for verification and augmentation. A list of the robots included in the survey is given in Appendix III.

RESULTS

The survey dealt with 86 identified development cases, and 76 answers (88%) were received from Japan, the U.S., Ger-

J. Constr. Eng. Manage., 1998, 124(1): 31-41

many, the U.K., Finland, France, Israel, and Sweden (a breakdown is shown in Fig. 1). Of these developments, 61 (80%) were reported by private companies and 15 (20%) by public institutes. Two major groups of respondents could be distinguished. One involved researchers in academic institutions who seldom exceeded the prototype stage and never the testing on-site stage. The other included contractors who developed the robots (sometimes in conjunction with equipment fabricators) and in all cases brought them at least to the testing on-site stage.

Altogether at least 15 intended applications were identified: floor finishing; exterior wall painting, quality control (mainly exterior walls); board installation; load handling (interior and exterior); brick, or block, masonry; welding; connecting; cleaning; fireproofing or steel painting; painting interior walls; tiling; reinforcement installation; concrete handling; clamping; and "other." A breakdown of these applications is given in Fig. 2.

The configuration of the robots are given in Fig. 3. Almost all the robots were developed for finishing activities; the rest, mainly for handling (which includes, skeleton-related activities).

About 68% of the replies referred to the control system; a breakdown is given in Fig. 4. Many of the respondents specified that their robots had some preprogramming options, although in many cases they were teleoperated. The number of intelligent robots (i.e., robots that include preprogramming ca-

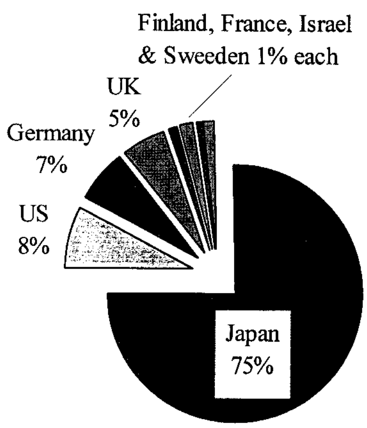

FIG. 1. Breakdown by Country of Replies to Survey (76 Total)

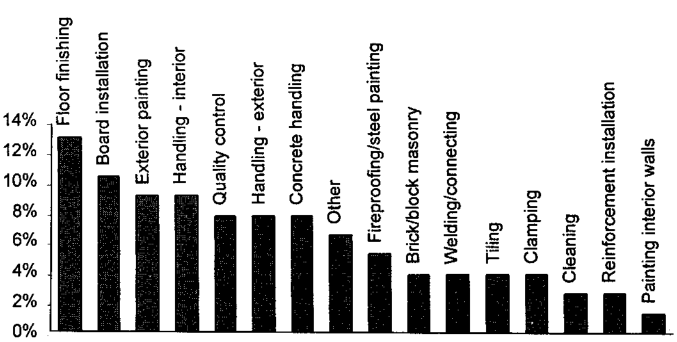

FIG. 2. Breakdown of Robot Applications (76 Total)

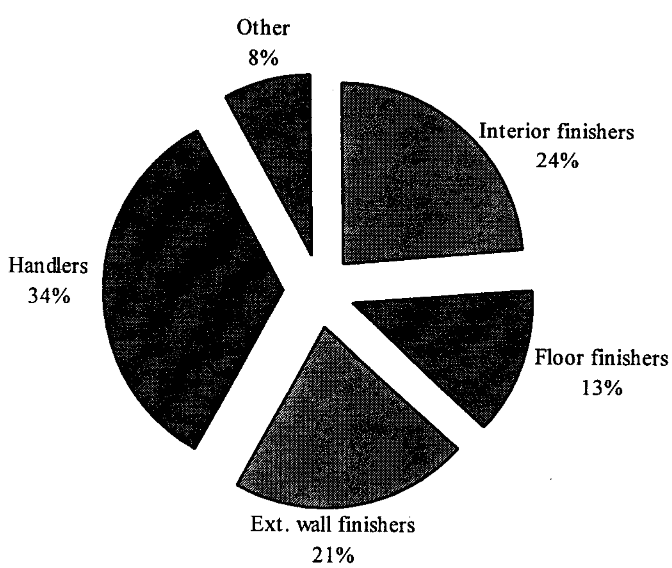

FIG. 3. Breakdown by Robot Configuration (76 Total)

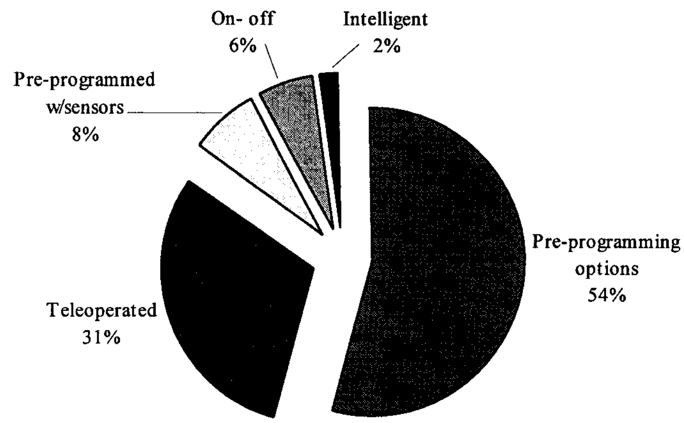

FIG. 4. Breakdown by Control System (52 Total)

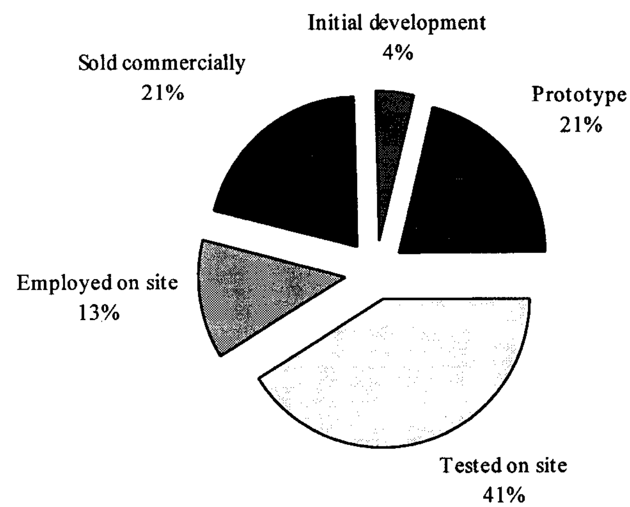

FIG. 5. Breakdown by Development Stages of Robots Surveyed (76 Total)

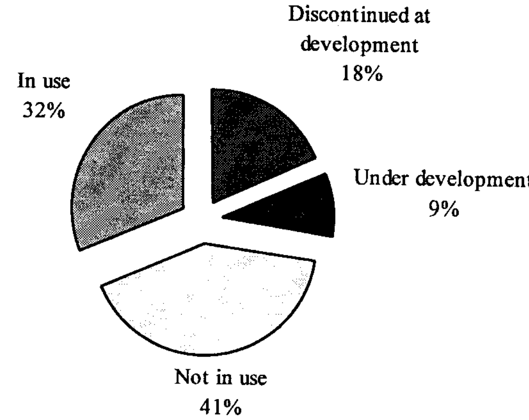

FIG. 6. Breakdown by Current Use of Robots Surveyed (76 Total)

J. Constr. Eng. Manage., 1998, 124(1): 31-41

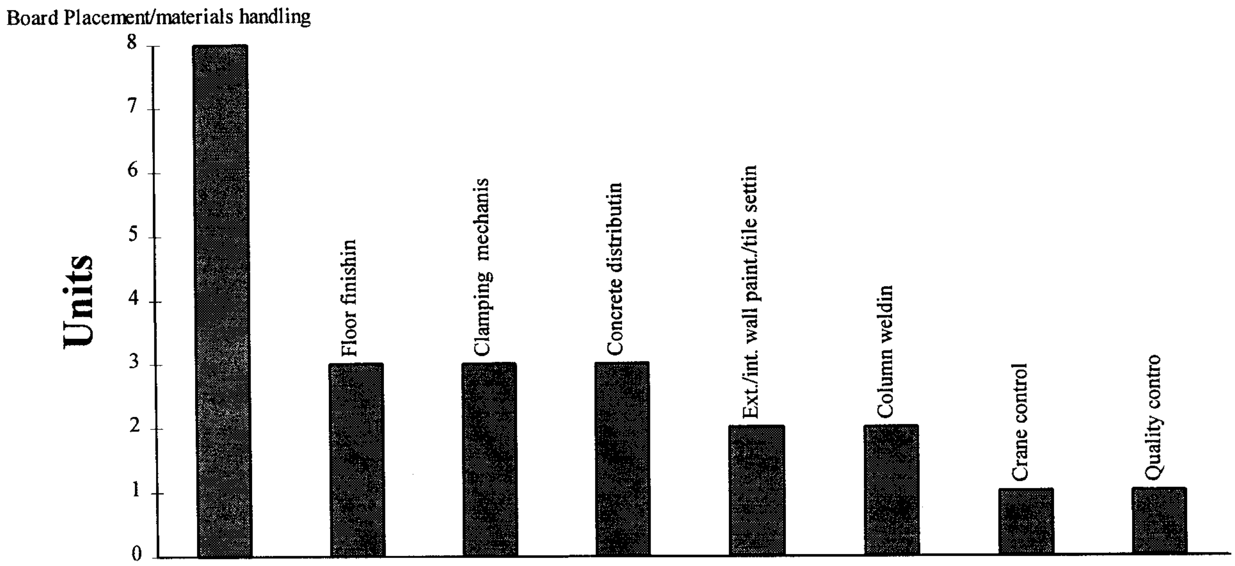

FIG. 7. Breakdown by Employment of Robots Currently in Use (24 Total)

pabilities and sensors) is almost negligible. The sensors employed were: ultrasonic, touch, tension meters, laser, optical, infrared, position measurement, pressure transducers, and inclinometers.

The stages of development of the surveyed robots were (a breakdown is given in Fig. 5):

1. Initial development: the development of the concept and some progress in the physical development at the laboratory
2. Prototype (off-site): the complete development of a prototype and its testing/employment in laboratory conditions
3. Tested on-site: one or more tests of the device in the conditions of a real construction site
4. Employed on-site: employed at least 5 times at a frequency of not less than once a year
5. Sold to others under commercial terms

Out of the total number of 76 investigated cases, 26 are or were employed on actual building sites, and 50 were never so used (apart from experimental purposes).

In terms of their current use, the cases were classified as follows (a breakdown is given in Fig. 6):

1. Discontinued during development (at predevelopment or a prototype stage)
2. Under development with some chance of implementation
3. Not in use, after being employed on-site
4. In use

Most of the robots currently in use are employed in board placement or material handling. A detailed breakdown of the employment of the robots currently in use is given in Fig. 7.

Most of the robots currently in use are teleoperated. As mentioned earlier, some respondents specified that their robots had preprogramming options, although robots were teleoperated. The breakdown of the control type of the robots currently in use is shown in Fig. 8.

As noted earlier, only about 34% of the robotic developments were employed on-site, at least to some extent. Ten (13%) of them were produced in five or more pieces, three (4%) in more than 30 pieces, and two (3%) in more than 100 pieces. Only 14 (18%) were used on-site 10 or more times, three (4%) were used 50 or more times, and two (3%) in more than 100 sites.

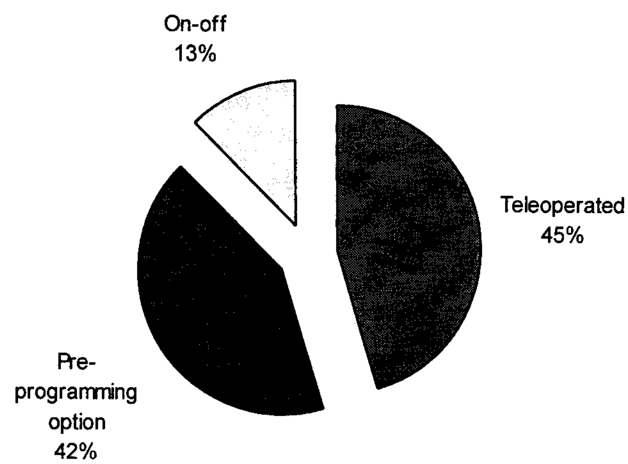

FIG. 8. Control Types of Robots Currently in Use (24 Total)

Almost all the robots still in some use today are either material-handling robots or floor-finishing ones. Most of these robots are operated under direct continuous human control.

The reasons developments or employment were abandoned are as follows (most frequent reason at the top and the least frequent at the bottom). There is no percentage breakdown, because many respondents cited more than one reason.

1. Lack of appropriate building sites
2. Need for further development/adaptations
3. Lack of economic justification
4. Lack of interest of the company's management
5. Availability of better equipment for the same function
6. Conservatism of potential users
7. Problems with material supply

DISCUSSION OF FINDINGS

Although the survey included all the development cases reported in the literature, the subsequent discussion focuses on the reasons for not using those prototypes that were already tested or employed on actual building sites. The survey asked for general reasons and, for practicality, did not attempt to study in depth the background of each particular case. However, it was found necessary to discuss in more detail the general difficulties of implementation of robotized construction in the various problem areas emerging from the survey, taking into account the particular features of the construction envi-

J. Constr. Eng. Manage., 1998, 124(1): 31-41

ronment and the inherent constraints of the robotic hardware. The paper attempts to define the conditions under which these difficulties can be mitigated to an extent that significantly enhances the chances of successful implementation. The following discussion of the findings and the ensuing conclusions are based partly on other studies carried out by the authors (Warszawski and Navon 1991; Warszawski and Rosenfeld 1994; Warszawski et al. 1996; Argaman 1990, unpublished D.Sc dissertation), which mainly explored the economic and functional aspects of robot usage, and partly on their many discussions with managers of construction companies.

The findings of the survey reveal that the application of robots to building construction is still at a very preliminary stage. Only a very small percentage of the robots (3–4%) could show through their production numbers to date or extent of employment (construction sites) a reasonable promise of firm commercial viability. This very meager success of application can be explained by the following main reasons, as reflected in the responses to the questionnaire:

1. Insufficient development of construction robot prototypes
2. Insufficient attention in building design to the constraints of robotized construction
3. Insufficient economic justification for robotics in building (which also includes the availability of better equipment)
4. Difficult managerial environment

Insufficient Development

The first and foremost difficulty in the employment of construction robots stems from the nature of construction work. Most construction tasks require mobility, sturdiness, large effectors, and the capacity to lift heavy loads. The robots that have been developed to date are therefore understandably big and heavy. Their present weight prevents them from being employed in residential, office, and similar buildings, which in most countries constitute 70–80% of the total building volume, and under normal conditions are designed for loads of 150–200 kg/m^2. Moreover, the robots, because of their size, find it difficult to enter and operate in small spaces that are characteristic of this type of buildings.

Most of these robots are powered by electricity supplied from an external source, which also very much restricts their movements. Furthermore, the majority of construction works require a continuous supply of materials that are bulky, ill-structured, and difficult to place at the precise locations required by a robot.

Most of the development efforts made at various places were mainly concerned with the effectors and control systems of the robots. They did not pay enough attention to aspects such as weight, maneuverability, completeness, and ease of operation. Good examples in this respect are the many development endeavors concerned with bricklaying or tiling where actual productivity gains could be achieved (as explained later) if the robotized operation were properly planned. However, in these works the main emphasis was on the block-placing proper, while other important issues, such as the attachment of blocks to each other, their continuous supply to the robot, and the robot's movement and maneuvering in limited spaces, were overlooked.

Unsuitable Building Design

The second reason for the failure to implement involves the adaptability of the building design to the constraints of robotized construction. The design must enable the robot to move freely and perform its work within the designated location of walls and partitions. It must also allow easy movement between work areas in terms of passage through doors (a sufficient width of at least 0.90–1.00 m), a simple path (not too many turns), and convenient transfers of the robot between floors and buildings (for exterior handling equipment). All locations that cannot be accessed by a robot within these constraints have to be completed by a human worker with more or less conventional methods. The greater such additional involvement of human labor, the less feasible becomes the special organization necessary for robotic work.

The same applies to the building exterior; a robot can be conveniently employed for painting or inspection of the building exterior if the building surface is adapted to robot movement, i.e., if the surface is smooth and the protruding elements or openings, if any, are well within the capacity of the robot to handle. All the exterior finishers need these types of surface to be efficiently applied.

Almost all the applications reported or demonstrated did, indeed, feature such large and unobstructed interiors and exteriors of buildings. However, standard construction comprises mainly residential and similar buildings (dwellings, hotels, health institutions, small office buildings etc.), which in some countries amount to 80–90% of the total construction volume. Such buildings are composed of small interior spaces and irregular exterior surfaces and, if not specifically adapted, are not suited to robotized construction. Very little work has been done to define the design rules that will create robot-friendly environments in different types of buildings and to apply these rules to the selection of buildings suitable for robot employment.

Another aspect of design involves the building technology. The conventional technologies of brick-laying, block-building, tiling, wiring, etc., are adapted to manual work, which has great flexibility in using several activities (finding, picking, placing, attaching) with different tools and materials for the same task. Such flexibility is unfeasible in robot construction, and the technology of their performance must therefore be simplified so that performance can be carried out in a single "pass" with a single tool and a single type of material. For example, the regular bricklaying method should preferably be so simplified that the bricks can be laid out in a single robotized operation, possibly without adding mortar or glue. Again, very little has been done to develop technologies that are robot-friendly in this sense.

Inattention to Economic Aspects

The development and design difficulties described here must be seen in their economic context, since the economics of robotized construction (i.e., the benefits of use versus the costs) ultimately determines its viability as a realistic alternative to the conventional building methods.

The costs of robotized construction include the direct (product-related) and indirect (time-related) cost of the robot, the cost of the operator who supervises the robotized work, and the cost of adaptation or modification of the construction method in view of the robot's constraints. These cost components were analyzed in Warszawski and Rosenfeld (1994) for several types of building works.

The economic benefits of a robot's employment include "tangible" and "intangible" benefits. The "tangible" benefits are associated with productivity gains relative to manual labor. These gains can be readily recorded, documented, and translated into money savings in labor costs.

The "intangible" benefits include improved safety, higher quality, and dependability. They also have a prominent economic value-avoidance of quality defects, accidents, and work stoppages. In many industrial applications these benefits, and not productivity gains, are the main reason for the employment of robots (Smith and Wilson 1982), but in as volatile an environment as a building site they are much more difficult to measure and evaluate. A construction robot is therefore ex-

J. Constr. Eng. Manage., 1998, 124(1): 31-41

pected, by its potential users, to justify its employment purely on productivity grounds. Moreover, since in the highly conservative construction sector technological innovations are always viewed with a certain measure of distrust, the economic productivity gains must be very significant in order to convince the prospective users.

In order to compete with manual labor, a robot, as shown in Warszawski and Rosenfeld (1994), must be employed 1,500–2,000 hours annually and replace 2.5–3.5 workers, depending on the prevailing wage for manual labor.

Such gains in productivity are difficult to attain in well-structured jobs—smoothing, painting, grinding—which are usually mechanized to a certain extent, even when performed in a conventional manner. The robot often uses the same mechanized tools as a human worker, and significant gains in productivity are therefore difficult to realize. It is doubtful, for example, that an automated concrete troweling robot (let alone a robot operated by remote control) using a rotary blade as its effector, can successfully compete, on the basis of productivity gains only, with a human laborer using a similar mechanical rotary blade.

The required gains in productivity may, however, be achieved (Warszawski and Rosenfeld 1994) in less structured construction tasks, such as bricklaying, partition building, and tile-setting, if large enough stretches of work are ensured. Here the robot can compete with humans in tasks that are not mechanized and can do them faster and without any decline in productivity due to fatigue over long periods of time. The realization of these savings in this type of work, however, requires the further development of the present prototypes and a sufficient supply of appropriate building layouts to ensure a robot's continuous employment. This last condition is particularly difficult to satisfy at present.

It follows, therefore, that for economic reasons the robot has the best chance of implementation in conditions that place a special economic premium on its "intangible" assets.

The employment of robots has a distinct advantage in conditions hostile to humans—physical hazards or extreme climates. However, few building projects are carried out in such conditions, and even then it may be easier to erect the shell of a building, insulate it from the outside, and proceed inside under normal conditions, rather than create the necessary economic and technological environment of robot employment.

Managerial Difficulties

The economic and technological difficulties are compounded by the managerial attitude in most construction companies. Construction managers tend to be highly conservative with respect to innovations. Construction is a risky industry, and managers are reluctant to add another risk factor to those already inherent in their work. To be accepted, an innovation must be either ideally applied in other places, which it is not yet the case with robots, or it must be very convincingly justified in tangible material terms. It is reasonable to assume that to overcome managers' reluctance to venture into something new and unknown, the robot must demonstrate the promise of a commanding profitability edge over conventional manual methods—and that, under present-day conditions, is impossible to attain.

Moreover, the employment of robots mandates considerable reorganization of a building site. It requires, among others, an easy transfer of the robots (bulky machines sensitive to damage) between buildings, building floors, and all locations on a floor. A clean and smooth floor surface in the path of the robot must be provided for its movement, which is not an easy task considering the nature of construction work and the materials used.

It also requires a continuous and convenient supply of building materials, such as paint, blocks etc., to robots at each work station, at precisely predefined locations easily accessible to the robot. For example a robot engaged in block building at a speed of one block (0.08–0.10 m^2) per minute must have at each station of 8–10 m^2 of wall a ready supply of 100 blocks, which will be used over a period of 1.5 hours. When painting or plastering, a robot must have a continuous supply of finish material from an outside mixer, which involves very frequent moves of the supply hose from one wall opening to another.

If the robot is to be employed automatically and not continuously guided by an operator, tolerances of the building infrastructure that are much tighter than for conventional construction must be demanded, to permit programmed access of a robot to work areas and building materials. Such tolerances in buildings are, to date, an exception rather than the rule in construction projects.

The employment of a robot under such circumstances, even for a single function, cannot be left to a foreman or a subcontractor, who is responsible for any particular function (e.g., painting or tiling), but must be placed under the direct responsibility of the site manager in such matters as preplanning, transfers, coordination, physical flow of materials, and maintenance of supporting procedures, which are all essential for the robotized work to succeed. It is difficult to imagine that such support is forthcoming, given present organizational practices and objectives of construction ventures.

When all these factors are added up—the shortcomings of development, the problem of appropriate design, the economic difficulties, and managerial apprehensions—it becomes clear why robotization has not yet established foothold in the building market except in some selected applications. In these the development and employment of robots have been defined as strategic objectives of the company concerned, largely divorced, even in the long range, from tangible economic profits. The employment of the robot, once developed, has been pursued mostly under especially favorable conditions in "friendly" projects organized with due regard to the robotic constraints, under a management effort explicitly oriented toward such application.

THE FUTURE

In the light of this bleak present status, is there any future for robotized construction? The answer is, by all means, yes, but only if the subject is approached in the proper manner. Let us consider again the four problematic areas that were discussed in the previous section.

Development

The robot has to be "site-friendly," i.e., well adapted to the particular conditions of the building site. This involves:

1. Its performance as a system. All aspects of operation, movement, materials feeding and transfer, and their adaptation to the particular conditions of a building site, must be taken into account in the development
2. Ensuring that its weight does not exceed the permitted live load
3. Its maneuverability, i.e., its work capacity in restricted spaces
4. Its versatility, i.e., ability to perform different tasks, increasing the extent of its use
5. Its independence with respect to power and materials supply
6. Its sturdiness, i.e., the ability to operate in the rough conditions of the building site with minimal maintenance requirements

J. Constr. Eng. Manage., 1998, 124(1): 31-41

Robots developed with due attention to these requirements will have a much better chance to survive.

Building Design

The building should be as "robot-friendly" as possible, with due regard, of course, to its basic functions. It has mainly to do with the following three subjects.

First, the robot can be used efficiently in large unobstructed spaces in the interior and on the exterior of the building. Since the availability of such buildings may not suffice for full employment of the robot, an effort must be made to adapt buildings with smaller interior spaces to robotized constraints. The best solution in this respect is to design buildings with entirely open interior spaces which, after the interior robotized work is completed, will be divided into the required secondary spaces by light partitions with their finish included, inserted into place by a robot or a human laborer.

Second, as far as building exteriors are concerned, large and unobstructed areas should also be provided for the robot. Their monotony can be relieved by application of an aesthetic exterior finish, which can be readily effected by a robot. Appropriate standard details for openings must be developed in view of the constraints of the exterior finishing robots. Such details, if widely applied, promise sufficient volume of work for exterior finishers will adapted to these standard details.

Finally, due attention must be paid to the selection of an appropriate building technology to simplify ill-structured (for the robot) building tasks. The examples in this field include one-layered coating, brick-building, tile-laying with simplified attachment requirements, etc.

Economy

Robots should be developed with due attention to the value added by their use. The best chances of economic application exist in countries that suffer from a severe scarcity of local labor and as a matter of national policy will not import foreign labor. In such countries the market drives labor costs to such levels that the employment of robots becomes feasible and even essential.

Additionally, the following "niches" of robot use should be exploited.

1. System building for a particular type of buildings, well adapted and designed with proper attention to specific requirements of the robots (as explained previously), preferably multipurpose robots.
2. High-precision tasks such as coating built surfaces: painting, fireproofing, and plastering. The precision of a robot's work can provide the necessary layer of covering at a lesser input of material—a distinct advantage, since the material constitutes a major part of the cost of work in this type of construction tasks. For example, a tightening of tolerance in painting from 2 to 1 mm when the minimum required thickness is 5 mm can reduce the material input by about 20%.
3. Sophisticated tasks involved in the intelligent application of sensors, and interpretation of the results, such as nondestructive quality control tasks, which can be done by robots equipped with visual or physical devices in a much more objective and reliable manner. For example, mapping of reinforcement in existing structures and identification of faulty tiles on a wall, corrosion on reinforcement, blemishes on prefabricated cladding, can be done by a robot faster and more reliably than by humans.
4. Particularly hazardous or dirty work—the fireproof coating of steel, the painting of a building's exterior, the assembling of structural steel elements, underground work, etc.
5. Employment of small and agile robots in restricted spaces by working in tandem with human operators. Robots would be assigned the harder manual tasks, such as lifting heavy objects or reaching to the floors and ceilings; humans would perform the more elaborate finishing touch. This can succeed if due attention is paid to the configuration of the robot and the various logistic problems involved in the supply and handling of bulky building elements in the restricted spaces.

Managerial Support

It is, however, inconceivable that robotized construction can succeed without very active and knowledgeable managerial support. The managerial involvement is essential in:

1. The choice of projects appropriate for robot application.
2. Long-range planning for the continuous supply of economically feasible building sites.
3. Careful planning of the site for robotized construction in terms of material supply, unobstructed robots movement, and robots transfers.
4. Enforcement of procedures suitable for robot operation and maintenance. (Here the inclusion robotics education in the teaching curricula of engineering schools is essential to the success of this task.

When all these aspects are addressed, robots will have a viable and promising future in building construction.

CONCLUSIONS

It may be concluded that robots in construction are still very much in an exploratory stage. They have so far been employed only in very large companies as a continuation or extension of their development effort in this field, motivated by the pursuit of a technological innovation and the expectation of far-reaching strategic future benefits rather than by present profitability or managerial expediency.

In most cases, the robots used at present need further adaptation to the nature of construction work in terms of their weight, maneuverability in small spaces, on-board power source, and materials supply.

With regard to design, attention should be given to the provision of large unobstructed interiors, exterior surfaces with well-adapted opening details, and properly selected construction technology.

The economy of robot use requires a sufficient volume of appropriate work for their continuous employment. The main justification for such employment will probably be scarcity of local labor and the explicit and hidden cost of importing foreign labor. At present the robots can be economically employed in the construction of repetitive buildings designed with due regard for robotic constraints, in sophisticated and high-precision tasks, and in dirty and dangerous building chores.

Ultimately, even when economically feasible, the success of robotized construction will depend on the support it receives from the project management. The management must very carefully choose suitable projects for robotized construction direct the design of these projects in the light of robotic constraints, plan the robots' employment on-site, and give them the necessary support during construction.

ACKNOWLEDGMENT

The writers wish to thank all the participants of the survey (listed in Appendix III).

APPENDIX I. QUESTIONNAIRE FOR FIRST STAGE OF SURVEY

1. Is (*please add the robot's name here*) ________________, which you have developed:

   In the development stage?
   A prototype (developed but not yet tested/used on-site)?
   Tested or had limited use on-site?
   Used commercially on several sites?
   Sold/leased to other companies?
   Other ________________

2. If the robot is in the development stage:

   In what year did the development start? ______
   Is the development completed? ______ When was it completed? ______
   What are the chances for implementation?
   - Good.
   - Not good.

   If the chances for implementation are not good, is it because of:
   - Lack of funds for further development?
   - Lack of candidate building for practical implementation?

   Lack of further interest of the sponsor?
   Other ________________

3. If the robot has been tested or has had limited use on-site:

   When was the development completed? ________________
   When was the robot used last? ________________
   How many times was the robot used? ________________
   Is the robot assigned to another site in the near future? When? ________________
   If not, please specify the reason:
   - Lack of an appropriate building site.
   - Need for further development/adaptation.
   - Lack of economic justification. (Please elaborate if possible.) ________________
   ____
   - Lack of interest of your organization.
   - Availability of better equipment for the same function.
   - Problems of material supply.
   - Conservatism of potential users/customers toward the finished product.
   - Legal barriers.
   - Other ________________

4. If the robot has been commercially used on-site:

   When was the development completed? ________________
   On how many sites was the robot used to date? ________________
   Is the robot used at present? If not, when was it used last? ________________
   Was it sold/leased to other companies? (Yes/No.)
   How many robots were sold? ________________
   The robot is used mainly by:
   - Contractor(s).
   - Subcontractor(s).

   If the robot is not used at present, is it because of:
   - Lack of appropriate building site.
   - Need for further development/adaptation.
   - Lack of economic justification (Please elaborate if possible.)
   ____
   - Lack of interest of your organization.
   - Availability of better equipment for the same function.
   - Problems of material supply.
   - Conservatism of potential users/customers toward the finished product.

J. Constr. Eng. Manage., 1998, 124(1): 31-41

- Legal barriers.
- Other ______

How many pieces of the robot have been produced to date?

______

Do you intend to continue producing the robot
- Immediately?
- In the future?

5. Automation level: ______

   10 Teleoperation
   11 Programmable with human intervention
   12 Fully automated
   13 Fully automated, interacting with the environment (sensors)

6. Does the robot use sensors? ____ How many? ____ Type ______

7. Number of axes/degrees of freedom (DOF): ______

APPENDIX II. VERIFICATION AND AUGMENTATION TABLE FOR SECOND STAGE OF SURVEY

Name	
Application type	
Level of automation	
Use of sensors	
Development completed (year)	
Number of sites used	
Year last used	
Number of robots produced	
Number sold to others	
Used by (general contractor/subcontractor)	
Used presently	
Reasons for not using	
Number of years used	
Comments	

Application Type

Structure

Steel

1101 Stud welding
1102 Painting
1103 Structural diagnosis
1104 Material handling
1105 Load balancing
1106 Column welding
1107 Fireproofing
1108 Clamping

Concrete

1301 Rebar production or handling
1302 Concrete pumping or distribution
1303 Structural diagnosis
1304 Material handling
1305 Screeding
1306 Concrete leveling
1307 Loading balancing
1308 Rebar installation
1309 Troweling
1310 Cleaning
1311 Grinding
1312 Concrete board installation

Finishing

Interior

2101 Ceiling/wall board installation
2102 Painting
2103 Floor finishing
2104 Floor brushing
2105 Material handling
2106 Tile setting
2107 Masonry
2108 Multipurpose
2109 Clean room inspection

Exterior

2301 Painting
2302 Tile inspection
2303 Material handling
2304 Glass roof or window cleaning
2305 Wall inspection
2306 Board installation
2307 Tile setting
2308 Jet scraper

Level of automation: 10 = teleoperation; 11 = programmable with human intervention; 12 = fully automated; 13 = fully automated, interacting with environment (sensors)
Configuration: interior finishing (if), floor finishing (ff), exterior wall finishing (ewf), handling (h), other (o)
Control: on-off (o), teleoperated (t), preprogrammable (pre), preprogrammable with sensors (ps), autonomous (a)
Sensors: position measuring (pos), pressure transducers (pr), inclinometers (inc), touch (t), infrared (i), laser (l), optical (o), ultrasonic (u), tension meters (tm)
Development stage: initial (i), prototype (p), tested on-site (t), employed on-site (e), sold to others and used commercially (sc)
Current use: discontinued at development (dis), under development with chances for implementation (dev), not in use after being employed on-site (nu), in use (u)
Reasons for abandoning: lack of building site (lbs), need for further development (nfd), lack of economic justification (lej), lack of interest in organization (li), availability of better equipment (abe), problems with material supply (ms), conservatism of potential users (cpu), legal barriers (lb)

J. Constr. Eng. Manage., 1998, 124(1): 31-41

APPENDIX III. BUILDING ROBOTS INCLUDED IN SURVEY

Robot name (1)	Company (2)	Country (3)	Application type (4)	Configuration (5)
Tile setting	VTT	Finlanad	Tile setting	Interior finishing
Soffito	CSTB	France	Painting	Interior finishing
Emir	Kenforschungsc.	Germany	Load balancing	Handling
Crane control	Liebherr	Germany	Material handling	Handling
Rocco	Lissmac	Germany	Masonry	Interior finishing
Elevator	Modern tech	Germany	Screeding	Handling
M44-amc	Putzmeister	Germany	Concrete distribution	Handling
Tamir	Technion	Israel	Multipurpose	Interior finishing
Spraybird	Fujita	Japan	Fireproofing	Interior finishing
Paint spraying	Fujita	Japan	Exterior painting	Exterior wall finishing
Facts	Fujita	Japan	Concrete distribution	Handling
Fireproof	Fujita	Japan	Fireproofing	Interior finishing
Stacker lift	Fujita	Japan	Screeding	Handling
Ag low lift	Fujita	Japan	Screeding	Handling
Roller lift	Fujita	Japan	Screeding	Handling
Harubei	Fujita	Japan	Board installation	Handling
Troweling	Hazama	Japan	Troweling	Floor finishing
Tile setting	Hazama	Japan	Exterior tile setting	Exterior wall finishing
Mr38	Kajima	Japan	Rebar installation	Handling
Stud welding	Kajima	Japan	Stud welding	Other
Tile inspection	Kajima	Japan	Tile inspection	Exterior wall finishing
Structure diagnosis	Kajima	Japan	Structure diagnosis	Other
Mark II	Kajima	Japan	Floor brushing	Floor finishing
Conc distributor	Kajima	Japan	Concrete distribution	Handling
Tile setting	Komatsu	Japan	Tile setting	Interior finishing
Lh 30.50.150	Komatsu	Japan	Board installation	Handling
Ls 100	Komatsu	Japan	Board installation	Interior finishing
Forklift	Komatsu	Japan	Screeding	Handling
Kfr-I	Kumagai Gumi	Japan	Exterior painting	Exterior wall finishing
Ceiling board inst.	Kumagai Gumi	Japan	Board installation	Interior finishing
Radio control-just pita	Obayashi	Japan	Clamping	Handling
Aclamp&aclaw	Obayashi	Japan	Clamping	Handling
Clean room	Obayashi	Japan	Clean room inspection	Other
Wall inspection	Obayashi	Japan	Exterior wall inspection	Exterior wall finishing
Osr-1	Shimizu	Japan	Exterior painting	Exterior wall finishing
Glass roof cle	Shimizu	Japan	Window/roof cleaning	Exterior wall finishing
Concrete screed	Shimizu	Japan	Screeding	Floor finishing
Load balancer geo	Shimizu	Japan	Load balancing	Handling
Mobile screeding	Shimizu	Japan	Screeding	Floor finishing
Wet boy	Shimizu	Japan	Fire proofing	Interior finishing
Mat. handling	Shimizu	Japan	Screeding	Handling
Mtv-1	Shimizu	Japan	Grinding	Floor finishing
Column weld.	Shimizu	Japan	Column welding	Other
Multi-coater	Shimizu	Japan	Exterior painting	Exterior wall finishing
Cfr1	Shimizu	Japan	Board installation	Interior finishing
Ssr-3	Shimizu	Japan	Fire proofing	Interior finishing
Flatkn	Shimizu	Japan	Troweling	Floor finishing
Mighty shackl	Shimizu	Japan	Clamping	Handling
Rexy	Shimizu	Japan	Material handling	Handling
Rebar fabrication	Taisei	Japan	Rebar production	Handling
Painting	Taisei	Japan	Exterior painting	Exterior wall finishing
Ex. wall inspection	Taisei	Japan	Tile inspection	Exterior wall finishing
Wall board	Taisei	Japan	Board installation	Interior finishing
Floor finishing	Taisei	Japan	Grinding	Floor finishing
Col. welding	Takenaka	Japan	Column welding	Other
Horiz distrib	Takenaka	Japan	Concrete distribution	Handling
Screed	Takenaka	Japan	Screeding	Floor finishing
Surf-robo	Takenaka	Japan	Troweling	Floor finishing
Conc. dist. crane	Takenaka	Japan	Concrete distribution	Handling
Horiz. conc. distr.	Takenaka	Japan	Concrete distribution	Handling
Ext. wall tile ins.	Takenaka	Japan	Tile inspection	Exterior wall finishing
Jet scraper	Takenaka	Japan	Jet scraper	Exterior wall finishing
Ext. wall painting	Takenaka	Japan	Exterior painting	Exterior wall finishing
Mat. transportation	Takenaka	Japan	Screeding	Handling
Agm	Chalmers	Sweden	Grinding	Floor finishing
Curio 1	City University	U.K.	Exterior wall inspec.	Exterior wall finishing
Masonry	City University	U.K.	Masonry	Interior finishing
Robug II	Portsmouth Polytechnic	U.K.	Exterior painting	Exterior wall finishing
Window clean	University of Newcastel	U.K.	Window/roof cleaning	Exterior wall finishing
Trackbot	MIT	U.S.	Board installation	Interior finishing
Studbot	MIT	U.S.	Board installation	Interior finishing
Walbot	MIT	U.S.	Board installation	Interior finishing
Blockbot	MIT	U.S.	Masonry	Interior finishing
Robocrane	NIST	U.S.	Material handling	Handling
Ls manipulator	University of Texas at Austin	U.S.	Material handling	Handling
—	WASCOR	Japan	—	Other

APPENDIX IV. REFERENCES

Boles, W. W., Maxwell, D. A., Scott, W. D., Heermann, P. D., Yarborough, T., and Underwood, J. (1995). "Construction automation and robotics. Pathway to implementation." *J. Constr. Engrg. and Mgmt.*, 121(1), 143–152.

Everett, J. G., and Slocum, A. H. (1994). "Automation and robotics opportunities: Construction versus manufacturing." *J. Constr. Engrg. and Mgmt.*, 120(2), 443–452.

"Japan Takes Early Lead in Robotics." (1983). *Engineering News Record*, 211(3), 42–45.

Obayashi, S. (1992). *Proc., 9th Int. Symp. Automation and Robotics in Constr.*, Tokyo, Japan 63–72.

Ochoa-Franco, L. A., Haas, C. T., Dailey, C. M., and Traver, A. E. (1994). "Construction automation research database (CARD)." *Proc., 11th Int. Symp. Automation and Robotics in Constr.*, Brighton, U.K., 523–530.

Paulson, B. C. (1985). "Automation and robotics for construction." *J. Constr. Engrg. and Mgmt.*, 111(3), 190–207.

Poppy, W. (1994). "Driving forces and status of automation and robotics in construction in Europe." *Proc., 11th Int. Symp. Automation and Robotics in Constr.*, Brighton, U.K., 215–222.

"Robot." (1997). Britannica Online.

Rosenfeld, Y., Warszawski, A., and Zajicek, U. (1993). "Full-scale building with interior finishing robot." *Automation in Constr.*, 2(3), 229–240.

Skibniewski, M. J. (1992). "Current status of construction automation and robotics in the U.S.A." *Proc., 9th Int. Symp. Automation and Robotics in Constr.*, Tokyo, Japan, 17–24.

Skibniewski, M. J., and Russell, J. S. (1989). "Robotic applications to construction." *Cost Engrg.*, 31(6), 10–18.

Smith, D. N., and Wilson, R. C. (1982). *Industrial robot: A Delphi forecast of markets and technology*. Ann Arbor, Mich.: Books in Demand.

Ueno, T. (1994). "A Japanese view on the role of automation and robotics in next generation construction." *Proc., 11th Int. Symp. Automation and Robotics in Constr.*, Brighton, U.K., 633–640.

Ueno, T., Maeda, J., Yoshida, T., and Suzuki, S. (1986). *Proc., Int. Joint Conf. on CAD and Robotics in Arch. and Constr.*, Marseille, France, 627–633.

Warszawski, A. (1990). *Industrialization and robotics in building*. Harper & Row, New York, N.Y.

Warszawski, A. (1995). "Automation in construction: Implementation prospects." *Proc., 12th Int. Symp. Automation and Robotics in Constr.*, Warsaw, Poland, 17.

Warszawski, A., and Navon, R. (1991). "Robot for interior finishing works." *J. Constr. Engrg. and Mgmt.*, ASCE, 117(3), 402–422.

Warszawski, A., and Navon, R. (1996). "Survey of building robots." *Proc., 13th Int. Symp. Automation and Robotics in Constr.*, Tokyo, Japan.

Warszawski, A., and Rosenfeld, Y. (1994). "Robot for interior-finishing works in building: Feasibility analysis." *J. Constr. Engrg. and Mgmt.*, 120(1), 132–151.

Warszawski, A., Rosenfeld, Y., and Shohet, I. (1996). "Autonomous control system for the interior finishing robot." *J. Computing in Civ. Engrg.*, ASCE, 10(1), 67–77.

Whittaker, W. L. (1986). "Construction robotics: A perspective." *Proc., Int. Joint. Conf. CAD and Robotics in Arch. and Constr.*, Marseille, France, 413–422.

Whittaker, W. L., and Bandari, E. (1986). "A framework for integrating multiple construction robots." *Proc., Int. Joint Conf. CAD and Robotics in Arch. and Constr.*, Marseille, France, 480–488.

J. Constr. Eng. Manage., 1998, 124(1): 31-41