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REVIEW ARTICLE

Robotics in Civil Engineering

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Abstract: *Robots have been investigated for automation of construction, maintenance, and inspection of civil works since the early 1980s. This paper describes the progress of robotics in civil engineering from the early 1980s to the mid-1990s. It focuses on the environment and motivation for implementation of robotics, identifies key centers of development, identifies regional differences, and describes progress in key areas. It also traces the emergence and change of development strategies over time, it identifies practical achievements, and it identifies key developments for the future. It concludes that despite many false starts and setbacks, significant progress has been made, and significant changes are on the horizon.*

1 INTRODUCTION

Using robots to do the dirty, difficult tasks in construction and maintenance of civil works was an idea first expressed in the early 1980s. Understanding how robots will be used for this purpose has changed tremendously since then. Fifteen years ago, robots were stationary, relatively simple, programmable manipulators working primarily on factory floors. In the intervening period, several changes have occurred. Large initial investments in robotics in the early 1980s slowed down significantly by the mid-1980s and were being widely questioned by the late 1980s due to early robots' lack of flexibility.[9] Since then, flexible manufacturing has become a primary goal of robotics research, and robots have gained senses and intelligence. During this same period, many attempts have been made to develop and apply robots in construction and maintenance, with limited success. However, recent advancements and a resurgence in robot investments hold out the hope that robotics will soon have a significant impact on civil engineering practice.

By providing a sense of how, when, where, what, and why developments occurred, the short review of robotics in civil engineering presented here can allow the reader to gain some insight into the technology. A more immediate purpose is to provide some context for current developments in the area and to give some sense of what may happen in the near future.

Robotics in civil engineering have emerged primarily in construction, maintenance, and inspection; therefore, these areas in their respective order are the focus of this paper. It begins with a discussion concerning the motivation for using robotics in civil works and the challenges related to implementation. Progress and trends in key areas including enabling technologies, building systems, and development strategies are then described. Practical achievements are documented, and an attempt is made to anticipate the most influential future technologies and environmental changes. Differences among global regions are identified to qualify the discussion. Finally, conclusions are drawn and recommendations are made concerning the status, past, present, and future, of robotics in civil engineering.

2 MOTIVATION AND ENVIRONMENT

Characteristics of the civil works environment both encourage and discourage the use of robotics, and many of these

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characteristics change from region to region. Several aspects are discussed below.

2.1 Industry structure

In the United States, the construction industry is highly fragmented, both vertically and horizontally.[40,41] Owners, designers, constructors, suppliers, and labor are normally distinctly separate entities with sometimes conflicting objectives. Even the largest companies constitute only a small part of the construction market. At the same time, owners and local governments impose their own bodies of specifications and standards, which often conflict. Little money is spent on research. In western Europe, the industry traditionally has been fragmented along the national border lines, and only recently has new legislation been enacted lifting all restrictions on bidding and performing construction work on public projects throughout the member countries of the European Union. Central and eastern Europe, until the late 1980s, has been subject to almost exclusive governmental ownership and asset control of engineering and construction organizations. In Japan, most of the industry is dominated by a few large corporations that have highly coordinated technology-development programs funded by about 1% of the firms' earnings.

2.2 Concern for health and safety

Over the last decade, increasing inspection of construction sites by the Occupational Safety and Health Administration (OSHA), rising awareness of accident costs (in human and project terms), and rising litigation against owners by injured workers have led to a new safety ethic in the construction industry of zero tolerance of accidents.[20] Robotics can be used to reduce labor requirements or distance the worker from unsafe tasks and thereby improve safety.

2.3 Concern for the natural environment

Increasing environmental regulations have increased the costs associated with construction and maintenance of civil works. Robots can be used to better control the application and removal of hazardous materials such as lead-based paints.[1,38] The cleanup of hazardous wastes that started over a decade ago often requires extensive protective gear and procedures that decrease productivity to the extent that rather exotic robotic technologies become economically feasible for this work.[17]

2.4 Workforce trends

While the average age of construction workers in Japan is increasing, the average of American construction workers has remained relatively constant over the years.[15] However, retention of workers continues to be a problem in the United States and in Europe. Labor costs in construction have been steadily rising, while productivity rates have been declining. Automation and robotics may decrease construction performance costs, increase productivity in some areas, and improve retention of workers by making work less dirty, less physically demanding, and more attractive when measured by professional prestige.

2.5 The physical environment

Most civil works exist in outdoor environments that change constantly. Making complex machines, originally designed for factory floors, work in wide ranges of temperature, wind, and rain, overcome dust and dirt, and handle the large forces necessary in construction is at the very least challenging. This challenge was largely underestimated in the early 1980s as the first prototype construction robots emerged. As experience has been gained, as the military has opened up, and as equipment manufacturers have become involved, hardier systems have been developed.

2.6 The nature of construction activities

Construction activities have changed little over the centuries in the sense that each facility being built is unique, unlike manufactured products, and construction work is often more complex that it first appears. Commercial robots in the early 1980s were not suited to work that required sensing the environment and changing actions accordingly. Most were run by simple repetitive programs, and their lifting force would typically not exceed 20 N. More sophisticated, powerful robots now exist.

2.7 Demilitarization

With the end of the cold war, expenditures on the military are decreasing in the United States. As a result, more money is being spent on infrastructure, and research funds are being redirected to agencies such as the National Institute of Standards and Technology (NIST). Both moves promise several-fold increases in building and construction automation research funding by the government. This is likely to accelerate introduction of robotics into civil engineering.

Military hardware contractors had little interest in construction until recently; however, many are now applying their expertise in producing robust computing and sensor hardware to the construction industry. Examples of such technologies include "smart" hydraulic cylinders, laser radar range sensing, and milspec electronic components.

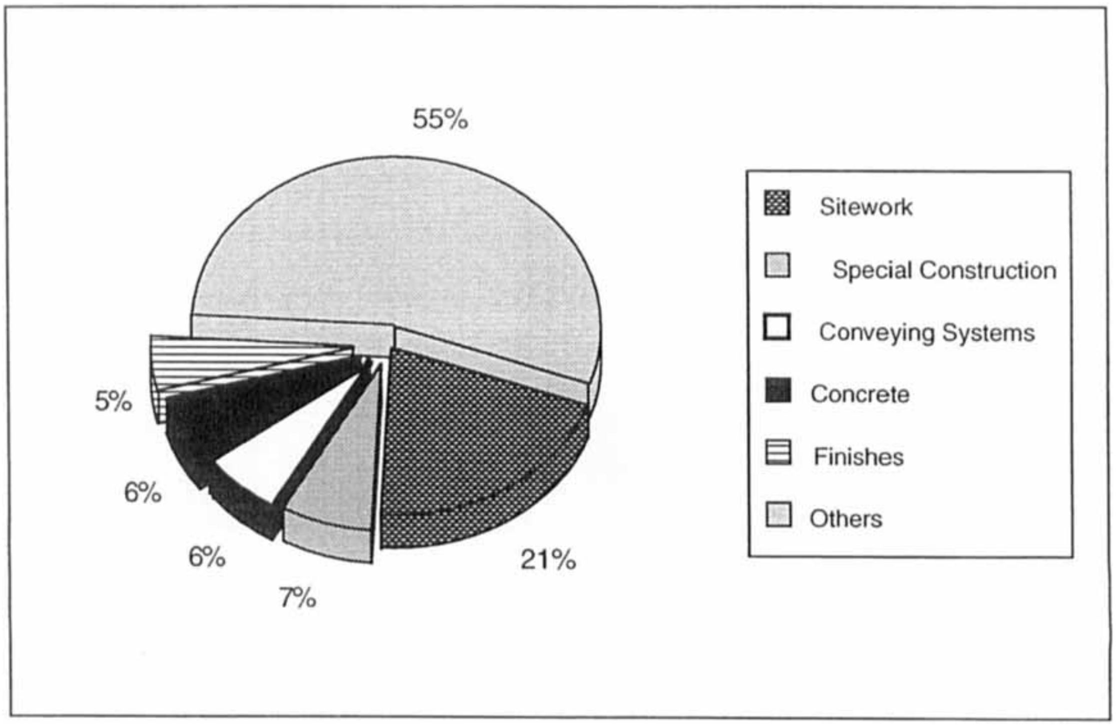

Fig. 1. ISARC Papers in Selected Application Areas.

2.8 International competition

GATT, the EEU, and NAFTA have opened international markets more than ever before. New technology can create strategic advantages for companies, and many construction companies are beginning to use their technological expertise to break into or dominate market segments. An example is the widely recognized Japanese expertise and technological leadership in soft earth tunneling. More companies are recognizing such advantages and are exploring the potential of robotics in construction and maintenance.

2.9 Robotics technology

Today's computers are hundreds of times more powerful than those which ran robots a decade and a half ago. With this increase in power comes many new capabilities. Complex software that can react quickly to several different sources of data in real time becomes possible. Huge amounts of visual, range, and other types of information concerning the robot's environment can be processed. Robots begin to have the capability to react to some of the changes encountered in the construction and maintenance of civil works.

Sophisticated feedback control systems for hydraulic cylinders promise controlability of large-scale manipulators. At the same time, direct electric drive has increased the capacity-to-weight ratio of electric-powered manipulators. Robots have steadily become smarter, stronger, and more sensitive over the last decade. They are leaving the factory and entering the outdoors.

3 CENTERS OF DEVELOPMENT

Perhaps the oldest broad-based forum for the presentation and exchange of information concerning robotics in civil engineering has been the eleven annual International Symposia on Automation and Robotics in Construction (ISARC). The first two ISARCs were held at Carnegie Mellon University (CMU), which is considered one of the birthplaces of construction robotics. In a recent study, papers from the fourth through the tenth symposia were classified and cross-referenced among several categories.[25]

Papers from the ISARCs can be grouped into technology areas, type of application (Fig. 1), or application domain. Each perspective adds insight into relative areas of interest and activity over the last decade. Data also can be arranged chronologically in such a way that trends occasionally can be observed, such as the decline of interest in artificial intelligence (AI) (Fig. 2). The ISARC proceedings also can be used to indicate which institutions and countries are or have been most active in construction robotics over the last decade (Fig. 3). However, other forums cannot be ignored,

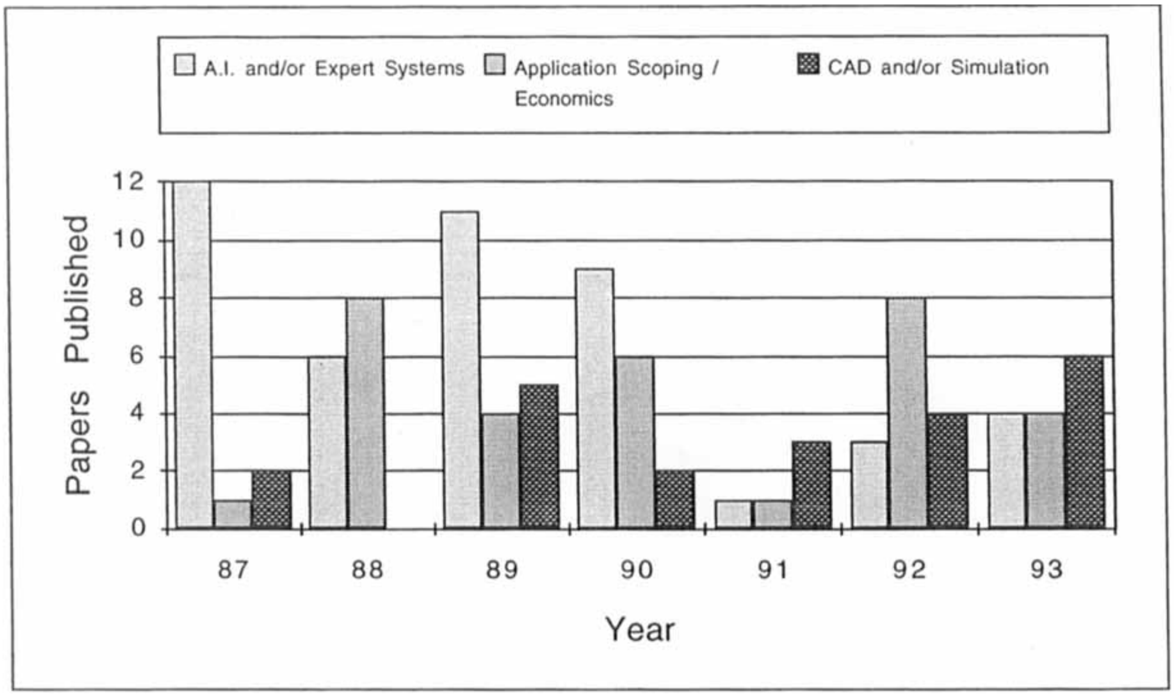

Fig. 2. ISARC Papers in Selected Technology Areas from 1987 to 1993.

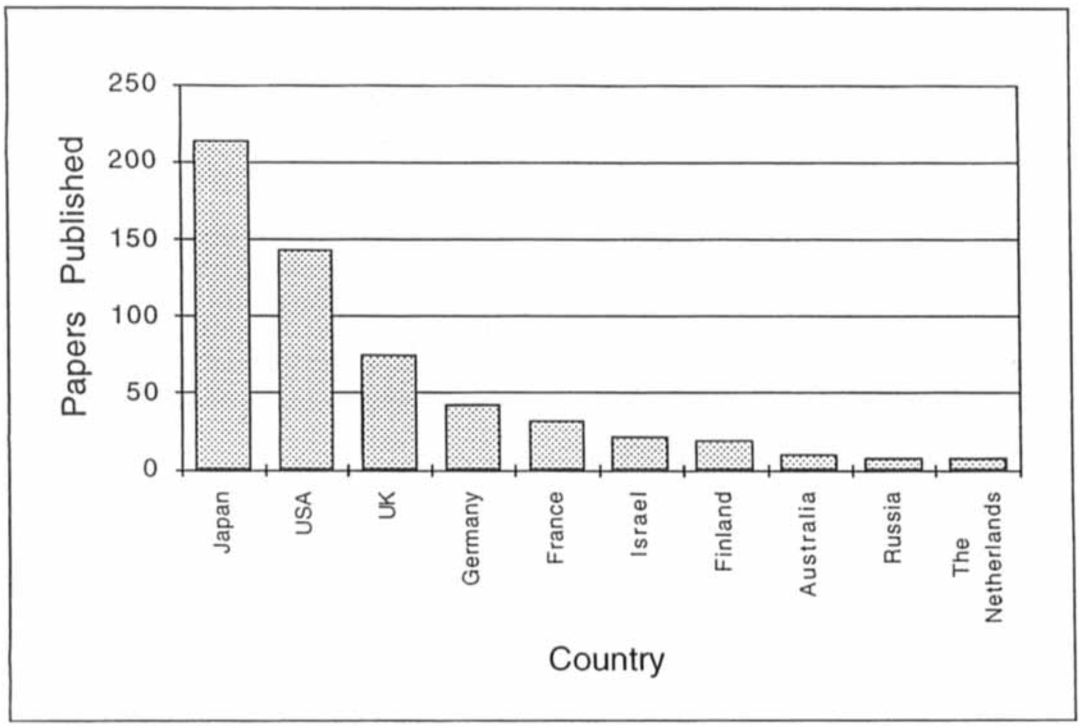

Fig. 3. ISARC Papers by Country of Origin.

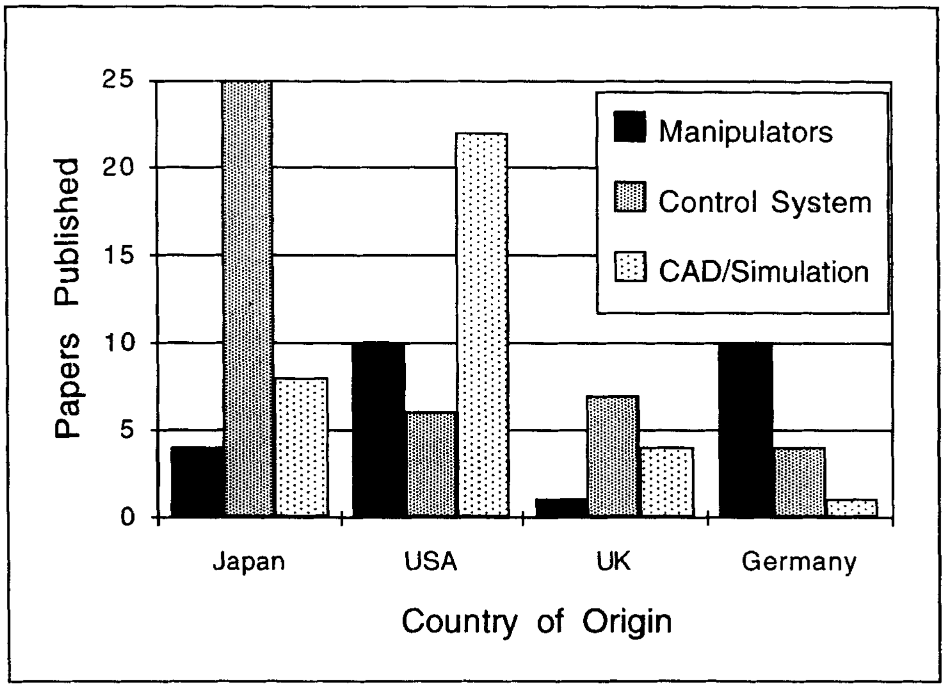

Fig. 4. ISARC Papers per Four Countries in Three Technology Areas.

and it must be noted that several very active corporations treat their developments in a proprietary manner that shuns academic forums. Their advances are normally noted in announcements in industry trade magazines or in product announcements.[10–12]

4 REGIONAL DIFFERENCES

Regional differences have been significant in construction robotics over the last decade. It is widely acknowledged that Japan has funded its construction robotics research efforts at the level of several hundreds of millions of dollars and has dominated the field since the early 1980s. Levels of research and development (R&D) funding in the United States, Europe, and other parts of the world have been at least a magnitude less than in Japan. Other important differences also exist. Each country may focus in certain technology niches (Fig. 4). Clearly, the United States has had a strong preference for CAD and software-oriented research, though the results may be biased by the lack of American industry publications in general. Results from the ISARC proceedings also indicate that R&D in construction robotics in Japan is industry-based, while in the United States it is largely based in the universities (Fig. 5).

In the United States, severe fragmentation of the construction industry seems to mitigate against any systematic introduction of robotics; however, this environment is also dynamic and competitive. It encourages innovation and change on a small scale. U.S. efforts to date to introduce automation and robotics into the construction industry have included limited government funding to stimulate R&D in this area. Research interest in construction automation was demonstrated by the National Science Foundation, which provided funding within its Construction Automation Program. Other governmental entities, such as the Environmental Protection Agency, the Department of Defense, and the Department of Energy, also have shown interest and have committed some funding for projects aimed at solving specific problems faced on various job sites by those organizations. New initiatives are on the horizon which plan to link private-industry sponsors with R&D laboratories for the purpose of developing new automated systems to handle a variety of problems on military and civilian project sites.

In western Europe, civil engineering as well as other robotics research and development is in large part coordinated by various international research programs (e.g., ESPRIT, EUREKA, COPERNICUS, etc.) financed by the European Union government and covering some of the major academic and technical research institutions in countries affiliated with the European Union. There has been significant interest in the concepts and products of this research among construction equipment manufacturers as well as a few contractors' federations and major engineering construction firms. Projects have varied from development of robotics for surface application and finishing to experimental systems for bricklaying, concrete placement, excavation, wall climbing, and others. Western European countries his-

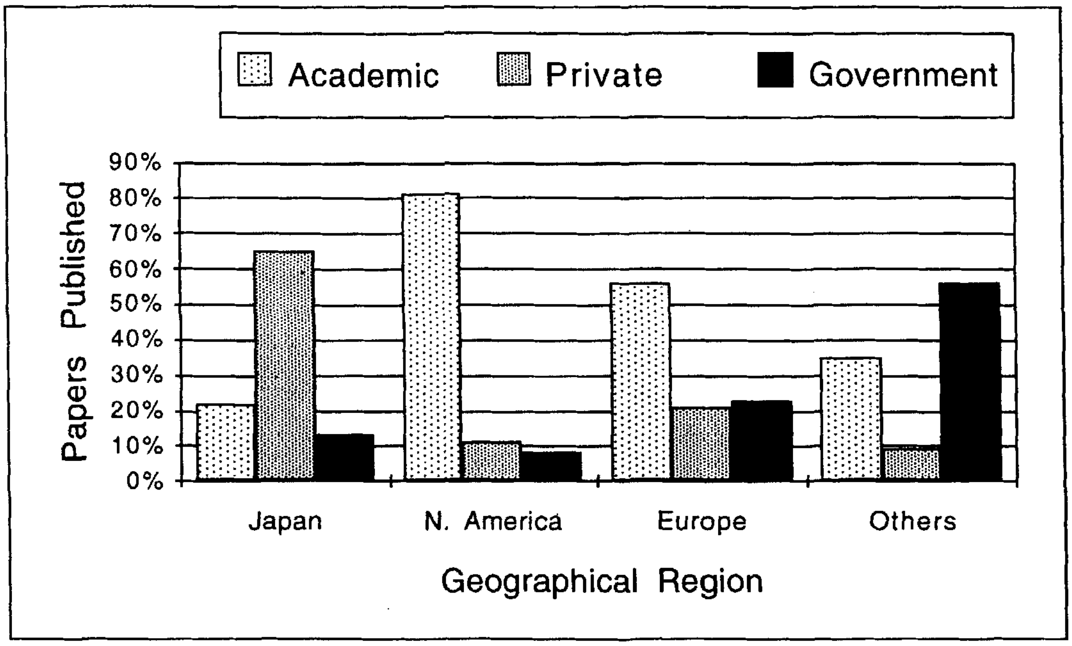

Fig. 5. ISARC Papers Institutional Sources by Regions.

torically most active in civil engineering robotics R&D include Germany, France, and Great Britain.

In central and eastern Europe, civil engineering robotics and automated components of conventional construction machinery have been researched and prototyped in government research institutes and academic institutions alike. The first civil engineering robotics R&D efforts, aimed at automated equipment for dangerous and difficult job-site tasks such as demolition work and automated load transport within hazard areas, were carried out in the former Soviet Union in the early 1980s.[3] A number of prototypical designs of construction robotic manipulators and entire robotic work systems were reported by construction equipment researchers.[13,14,42] Work on mathematical modeling and automated control of the excavation processes,[39] as well as of the excavating and loading equipment,[6] has been conducted in Poland since the mid-1980s. A number of these projects are being followed-up today. Examples of other related work include research on the automation of overhead gantry cranes for application in concrete prefabrication, partial automation of equipment-operator interfaces, and optimization of hydraulic drive usage.

Significant work has been conducted in Poland on the fundamental modeling of the evolutionary process of the design and use of construction equipment.[45] The emergence of construction robotics and automated construction processes can be viewed in this context as the latest development in the process of mechanization of cumbersome construction work tasks. Reflecting this evolutionary approach, Poland and other central and eastern European countries focus their efforts on the gradual improvement and redesign of existing equipment models and configurations, giving priority to proven and practical components of the robotic technology and human-machine interface solutions researched and developed to date.

Japan has attempted a more revolutionary approach to the introduction of robotics, requiring redesign of the construction work-site environment itself before robotic applications can become successful. Initially, several large engineering construction firms devoted large amounts of resources to the development of single-purpose construction robots.[26] However, intense competition among these firms led to a frequent duplication of effort in developing proprietary hardware that was similar to those of the counterparts in function and technological solutions. Follow-up efforts were eventually coordinated by Japan's Ministry of International Trade and Industry, which supplemented private company resources with government funds intended to support development of generic civil engineering and construction robotic solutions. Professional organizations within the civil engineering and architectural community formed groups whose purpose was the furthering of the robotics cause in the industry (e.g., Committee on Technology for Robotized Building Production of the Architectural Institute of Japan).[2] In addition, private company consortia teamed with major universities under the umbrella of the WASCOR project in the long-term development of construction robotic concepts and prototypical solutions.[37]

Recent development efforts have focused on the development of almost fully automated high-rise building construc-

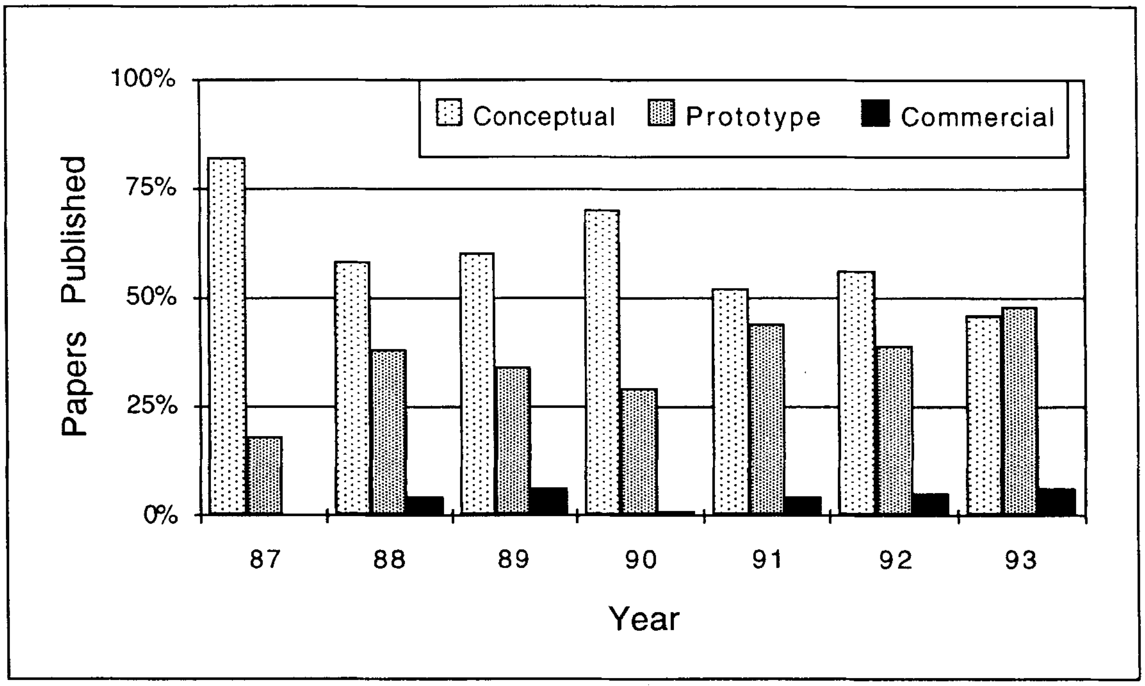

Fig. 6. ISARC Systems Papers by Level of Development from 1987 to 1993.

tion (ABC) systems that were commissioned, designed, and built by several major engineering construction companies, including Taisei,[30] Shimizu,[22] Obayashi,[33] and Takenaka. Other major Japanese construction firms have similar systems nearing design and prototyping completion or still under development. Similar features of these systems include self-raising platforms supported on hydraulic jacks, overhead gantry cranes and robotic manipulators suspended from the platform performing structural and nonstructural building assembly tasks, as well as horizontal and vertical materials handling systems. Several buildings throughout Japan have been constructed to date with the use of these systems. It has been claimed that some of these systems can reduce construction site labor requirements by up to 80% and reduce construction time by up to 50%.

5 PROGRESS IN KEY AREAS

One important indication of the progress construction robotics has made over the last decade is the absolute number of field and commercial prototype systems being described in the literature, as well as their number relative to descriptions of conceptual systems (Fig. 6). Well over 100 machines are now available on the market. This estimate, however, is complicated by the evolution, in the last 10 years, of sophisticated computer assistance and control technology for conventional construction machinery. The lines between robots and conventional construction equipment are becoming blurred.

5.1 Control systems

Most construction machines are powered by hydraulics and are manipulators of some sort. While many initial efforts in construction automation attempted to use factory-type, electric-driven robots to perform tasks such as masonry, current efforts are focusing on using computers to control construction manipulators such as excavators, loaders, and concrete pumps. This has been made easier by the introduction of electrohydraulic valves in the late 1970s. Control packages using computers are now commonly found in the product lines of major construction equipment manufacturers.

Software control now exists to economize on fuel usage, prohibit an operator from moving a joint past its limits, or diagnose trouble spots in hydraulic lines. Current R&D is focusing on the selection and installation of sensors that can measure flow rate, cylinder extension, pressure, and even deflection. With such information and more powerful control computers, attempts are being made to implement resolved motion control so that an operator can specify, for example, that he or she would like the excavator bucket to scrape horizontally or so a series of manipulator actions can be repeated with preprogrammed variations.[21,31] These types of control can reduce operator fatigue and improve operator productivity significantly. Tremendous challenges remain in terms of understanding the ergonomics of such control systems, developing nonlinear control, and controlling redundant and therefore mathematically indeterminate manipulators.

Variations on classic robotic control have fluctuated in the degree of interest they have generated over the years. Telechiric, or master-slave, control was used as early as the 1960s for manipulators used to handle radioactive wastes. A recent resurgance in such control systems is represented by an electric line worker manipulator and a tree trimmer.[4,16] These control systems depend on human visual feedback and force feedback in the control stick (or exoskeleton). A computer in the control loop is optional.

Teleoperated systems usually use video and audio feedback as well as control sticks and buttons at a remote operator workstation. Early systems were functional but were handicapped by lack of depth perception and peripheral vision, and they induced operator fatigue very quickly.[29] Efforts to correct these problems are focusing on relieving the operator by implementing limited robot autonomy.

Graphically controlled systems are currently being investigated as well, but they depend on the ability to generate an accurate model of the work space.[23] In the short term this may be difficult given the dynamic environment of most construction projects; however, survey and maintenance robots may take advantage of this approach.

A number of sophisticated control architectures emerged in the late 1980s that could be useful for controlling complex systems with many sources of sensor data and subprocesses. Current efforts are focusing on standardization, modularization, minitiarization, and cost reduction of control system components. An example is the CAN (controller area network) multiplexing scheme developed by Bosch and Intel.

5.2 Sensors

Sensor technology has changed in many ways since the early 1980s. New developments such as "smart" sensors that process sensor signals at or near the transducer have emerged. They represent a move to distributed and localized processing and control that is also represented by "smart" cylinders, for example, which have their own sensing and control modules afixed.

Because video sensors can now be packaged in boxes only a few centimeters on each side, and because computing power has increased, it is now feasible to fit robots with machine vision capabilities. Machine vision can be used to sense, model, and interpret the robot's environment, enabling it, for example, to avoid obstacles.

Affordable single-axis sonar and laser range sensors have been available since the early and mid-1980s, respectively. Such sensors have been used to model the contour of the surrounding terrain or build environment. Multiaxis range scanning using laser radar and millimeter-wave radar has declined in price as much as 90% from 1985 to 1994; however, it is still a relatively expensive option. These sensors are being used in autonomous vehicles, including automated off-road haul systems and highway work following vehicles.

Sensor data analysis has focused in the last several years on concepts of sensor fusion or integration, in which world models are constructed from multiple sensor types, locations, perspectives, and instances in time. Such techniques are powerful but complex and will require even greater computing power or optimization to become feasible in construction robots. They hold great promise for the future.

5.3 Graphic simulation and modeling

Graphic simulation and modeling are powerful analytical tools for designing construction and maintenance robots. Two-dimensional CAD has been affordable for many years. Three-dimensional CAD and solid modeling tools have been declining rapidly in price over the last few years and have now also become affordable. They can be used to train operators, experiment with control schemes in a safe and affordable manner, and communicate planned work sequences.[7,44] As graphic simulation and modeling have become more available, advances in construction robotics have accelerated.

5.4 New machines and mobility systems

Fantastic hybrid prototypes have emerged over the last several years that worm, walk, burrow, and fly about.[7,44] They represent the range of possibilities presented by robotic technologies, and it is difficult to assess their potential impact; however, at least two companies market small teleoperated robots that can inspect and repair sewers with diameters as small as 15 cm. Other "no dig" technologies are also emerging.[24]

6 EMERGENCE AND CHANGE OF STRATEGIES OVER TIME

Arguably, one of the most significant historical advances in civil works technology has been the concept of modularization. While the Roman brick may have been the first building module, modularization and prefabrication emerged in the construction of the Crystal Palace in London in 1850 and the Eiffel Tower in Paris in the 1870s. It has been used in housing and hotel construction and is becoming popular in industrial construction because it facilitates prefabrication and safer construction. It is closely related to the concept of designing for automation. Both concepts increase the feasibility of using robotics, because components have specified dimensions and easy connections.

Industrialization of building construction offers additional opportunities for the application of robotics.[43] From the General Houses consortium formed in the United States in 1932, to the Veteran's emergency housing program started in 1946, to Operation Breakthrough (1969–1973), attempts have been made to industrialize the building industry. Impediments are the nature of the industry and the failure to meet consumer expectations.[36] Many efforts continue, however, particularly in quickly growing regions of the world.[27] Robotics will play a large part in production and assembly of components for industrialized building systems.

While efforts to automate construction have shifted focus in the United States and Europe from distributing conventional industrial robotics about the construction site to enhancing and modifying existing types of construction equipment, Japan has taken a great leap into fully automated building systems. It is probably too early to evaluate the impact of this new approach on the construction industry.

7 PRACTICAL ACHIEVEMENTS

Based on the developments in construction and maintenance robotics to date, a number of commercial technologies that have changed practice and that were not in existance 10 years ago can be identified. Those which are now commercially available include, among others

- Resolved motion control for backhoes, manlifts, loaders, etc.
- Automated leveling and grading using lasers
- Tipping- and proximity-sensing systems for safety
- Automated sand blasting and painting systems
- Computer-controlled concrete placement pumps
- Advanced tunneling techniques

A number of robotics technologies are on the immediate horizon in terms of commercialization. They include, among others

- Autonomous off-road hauling vehicles
- Automated inspection systems
- Robotic bricklaying machines

8 KEY DEVELOPMENTS FOR THE FUTURE

Three-dimensional real-time position measurement will provide crucial input for construction, maintenance, and surveying robots. Several development efforts in this domain are underway. For example, several companies have formed a consortium led by the Civil Engineering Research Foundation (CERF) to develop a real-time 3D position-measurement system that is linked to a facility's CADD model.[10] This technology could revolutionize traditional surveying by eliminating such devices as grade stakes, batter boards, and plumb lines. As well, it can serve as crucial input for equipment control systems. Another consortium is attempting to develop a related technology. In the Pentagon's Technology Reinvestment Project's first round of awards, a team including Magnavox Electronic Systems Company, Spectra-Physics Laserplane, Inc., and the U.S. Army Corps of Engineers was awarded US$17.7 million to develop GPS and laser technology to control earth-moving equipment blades.[12] The team promises earth moving "to accuracies of a centimeter" without site and topographic surveys.

Another key development is in the domain of technology R&D financing. Consortia are becoming more popular as a means of combining the strengths of industry, academia, and government. The projects described above are examples of this trend. Current government R&D funding initiatives such as the U.S. Army Corps of Engineers' Construction Productivity Advancement Research (CPAR) Program will continue this trend.

9 CONCLUSIONS AND RECOMMENDATIONS

Robotics in civil engineering have progressed over the last 15 years through several phases. Initial research interest and funding in the United States in the early 1980s coincided with tremendous increases in investment in robotics in the manufacturing industry. A subsequent and abrupt slowdown in robotics investment in the mid-1980s coincided with initial results from construction automation research that illuminated the challenges of making robotics feasible in construction and maintenance. The spread of robotics to other industries in the late 1980s has foreshadowed their entry into civil works. The emergence of the first commercial construction and maintenance robots, only recently, has been precipitated by a number of factors. Enabling technologies such as computers have surged in power and plummeted in price. Past experience has begun to pay off. Government has enacted increasingly restrictive environmental regulations. Concern for safety has increased, and global competition is ever more intense. All these factors motivate the introduction of robotics, because robots can reduce labor requirements, improve safety, control emmisions, improve productivity, and improve flexibility.

Given the potential of robotics in civil engineering, the relative lack of investment in their development is surprising. Increased investment by government and industry is merited. An active organization devoted to the financial sponsorship of automated construction technology R&D is needed. Robotics implementation logistics and the optimal use of scarce robot equipment resources also must be considered.[35]

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