AUTOMATION AND ROBOTICS FOR CONSTRUCTION

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ABSTRACT: The potential for automated real-time data acquisition, process control and robotics for remote, large-scale field operations, such as those on construction engineering projects, is addressed. Classifications of technologies for automation and robotics in such operations include hard-wired instrumentation, remote sensing, analog and digital telecommunications, optical (laser, infrared and fiber-optic) data transmission, monitoring via microcomputer-based instrument control and data recording, on-site process control for fixed plants, partial or fully automatic control of mobile equipment, fixed-based manipulators, mobile robots, communications between on-site computers and automated machinery, electronic ranging and detection, and video-image pattern recognition. Combining selected technologies with microcomputer-based software could facilitate analysis, design and control decision-making, and could provide a means of coordinating various discrete automated components or machines that must work together to perform field tasks. This paper also mentions categories of needs for such technologies on field operations, and potential barriers to implementation. Progress will depend on the interest and support of researchers qualified to advance this field.

INTRODUCTION AND OVERVIEW

Factory-based manufacturing industries have long been enjoying increasing economic, safety, and quality control benefits from automated data collection and from the process control of production operations; robotics applications are being incorporated as a logical extension of this trend. However, field-oriented industries like construction, with frequently reconfigured operations and often severe environmental conditions, have been slower to adopt automation technologies, and have scarcely been touched by robotics, at least in the United States. This paper examines the reasons for this, and suggests remedial technologies and research. This is an exploratory paper and is not intended primarily to report research results or describe applications of the technologies being examined. The general purpose is, given both the technologies and the industries in which they might eventually be applied, to suggest how to build a bridge between them. More specific objectives are to describe the needs for and potential of these technologies; to review the state of the art in selected areas; to briefly define, examine and classify the various technologies; to suggest experiments in automated data acquisition and with mobile and fixed-base robotics devices to better understand their potential and limitations; to mention technical, economic and institutional barriers to making the technologies an attractive goal and practical reality for industries like construction; and to stimulate potential researchers with the qualifications and interests to advance this field.

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NEEDS AND POTENTIAL

Fast-changing, field-based, project-oriented industries like construction are severely handicapped by their lack of accurate, timely and systematic technical, cost, and production data from ongoing operations. This paucity of reliable information is decried in major industry studies, such as the Business Roundtable's highly publicized Construction Industry Cost Effectiveness Project (9,44). It also constrains the implementation of promising analytical methods, such as probabilistic estimating, stochastic scheduling, statistical quality control, and the computer-based simulation of operations.

Meanwhile, technologies have evolved that can not only monitor the ongoing operation of manufacturing facilities and collect operational and passenger volume data from transit systems, but can monitor vehicle operations characteristics, transmit high-resolution video images, and capture results of instrumented biological, chemical, and geological experiments from unmanned vehicles sent to probe the planets. Why hasn't more of this technology filtered down to meet the needs of relatively conservative industries like construction? Are there insurmountable problems with, or gaps in, the technologies themselves? Is there something about these more traditional industries that makes them inflexible to change? What new concepts or adaptations of existing technologies might help bridge the apparent gap between possibilities and reality? Why do some countries, such as Japan (18,32), seem to be moving more quickly to implement advanced real-time data acquisition technologies in construction?

Similarly, construction lags in production automation and robotics. Ref. 37, a report on the 13th International Symposium on Robots, states that "of the 260 robots on display, . . . not one was earmarked for construction applications." Furthermore, "conference exhibitors were not aware of any current job-site applications in the U.S." (37, p. 30). Although construction is considered by some to be the largest sector of the U.S. economy, robot manufacturers gave several reasons for shunning this market. According to David M. Osborne, technical director of Swedish ASEA's Troy, Michigan, office, "construction jobs are not always the same, so there's not a great deal of repeatability. Most construction jobs require a certain amount of on-site judgment, which a robot can't provide. And there are a lot of uncontrolled environmental factors. If I leave a robot out in the rain, I lose $100,000 by the end of the week" (37, p. 30).

David Wisnoski, group vice president of the Industrial Systems Group, based in Naperville, Illinois, commented that "where robots work best is where the environment is very structured. The construction industry . . . is very individualistic and resists this kind of thing. I wouldn't say people should be worried about their jobs yet—there won't be robots in their business for quite some time" (37, p. 30).

As outsiders to construction, these robot manufacturers quite perceptively identify the major technical and institutional issues that face field- and project-oriented industries. It is surprising, however, that robot manufacturers seem to be so easily discouraged rather than challenged by the problems they describe. First, robots by nature are programmable and thus should be adaptable to changing environments, rather than restricted to the repeatable, very structured tasks desired by present state of the art. Second, most construction jobs do indeed require more judgment than those in factories, but is this not then an area where the benefits of artificial intelligence and expert systems research (1,14) might best emerge? Finally, the environment is certainly a factor. But if ASEA's robots cannot handle even a week of gentle rain, what would happen during a winter on Alaska's North Slope; platform operations in the North Sea; working 1,000 ft underwater off the California coast; 120° F and sandstorms in the Middle East; or working 100 stories up framing steel on a cold winter day in Chicago? In many of these situations, robots could provide welcome relief from the safety and health problems construction workers face every day. Construction machinery is manufactured to cope with such environments, so surely construction robots could be as well.

In any case, the manufacturers are correct when they claim there are many problems to be solved, both basic and developmental, before automated data acquisition, robotics and process control technologies evolve to the state where they will play a significant role in industries like this. Many of these problems can make exciting long-term basic research topics suitable for researchers, if only they could be made more aware of the needs and characteristics of such industries.

Present State of the Art

Given years of research in the defense and aerospace industries, manufacturing, and related fields of science and engineering, a vast amount of work has been done on automated real-time data acquisition, process control and robotics, even for extraterrestrial applications, let alone for remote sites on earth. Construction researchers must start by exploring these fields and evaluating their technologies and research efforts for their potential relevance to construction needs and objectives. However, rather than attempt to review the vast general body of knowledge in data acquisition, automated process control and robotics, this section will focus primarily on related work in construction.

Automated Data Acquisition

The first set of paragraphs below briefly review the following main areas that relate most closely to automated data acquisition: (1) Video data acquisition; (2) computer-based data acquisition systems for field engineering operations; (3) automated monitoring of construction quality control; (4) automated monitoring of production rates and quantities for field operations; and (5) recording and processing collected data.

Video Data Acquisition.—The principal reference for applications of time-lapse photography, which preceded video data acquisition and operations analysis in construction, is *Methods Improvement for Construction Managers*, by Parker and Oglesby (29). Subsequent research to use microcomputers to partially automate the data extraction from film was conducted by Dorman, et al., in Australia (10) and Touran at Stanford (45). Basically, these methods require an analyst to focus in detail upon an ongoing operation to understand relationships between tasks and resources, quantify activity durations, determine sources of delay, and locate imbalances in the operation's design. Time-lapse film or videotape has advantages in reducing the labor required to capture data; they capture more data simultaneously; they allow repeated viewing of the operation for different parameters; and they enable time compression. More recent work in video data acquisition was conducted by O'Brien, et al., in Australia (28), and Paulson (35) and Koo (20) at Stanford.

Computer-Based Data Acquisition for Field Engineering Operations.—This is an area where our colleagues in structural and geotechnical engineering have made considerable progress, but few have integrated their analysis and design-based instrumentation into real-time construction engineering decision-making. Some contractors, Japanese in particular, have put considerable emphasis on integration, and rou-

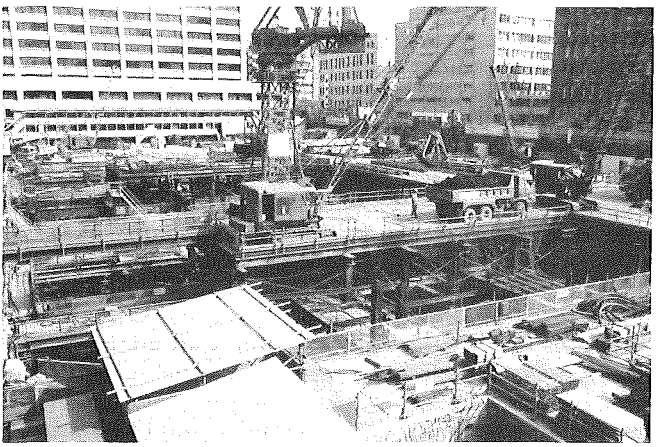

FIG. 1.—Instrumented Building Foundation Excavation in Japan

FIG. 2.—On-Site Minicomputer-Based Data Recording and Monitoring

tinely instrument and monitor deep foundation excavations, offshore works, tunnels, and similar structures (32). Fig. 1 shows a 34-m-deep foundation excavation for a building in Tokyo that had several hundred instruments installed. Fig. 2 shows the on-site minicomputer-based recording and monitoring system connected to the instruments. Such instrumentation is widely used by Japanese contractors to optimize major excavations.

Automated Monitoring of Construction Quality Control.—An early integration of data acquisition and quality control involved concrete batch plants, particularly under the stringent requirements of nuclear power construction. Other recent examples are point-of-placement concrete quality testing and a continuous weld quality monitor developed by the Army Corps of Engineers at its Construction Engineering Research Laboratory in Champaign, Illinois (4,36). The Corps has also used time-lapse photography to automatically record the coverage of compactors on earth-moving operations. Offshore platform construction projects, among others, have used various remote sensing devices to position piles and other parts of their structures. Lasers and other automated guidance technologies serve not only to increase excavation and grading production (33,46,47), but to significantly improve the quality as reflected in deflection and thickness. In general, however, this area is in its infancy in construction, and future research will draw much more from aerospace, defense, manufacturing and related higher technologies to explore potential.

Automated Monitoring of Production Rates and Quantities.—A number of mining operations have used sensors to count vehicles, such as trucks, to estimate production volumes, and even optionally to reroute trucks to idle loaders. The Japanese normally have automatic recorders attached to advanced soft-ground tunneling machines to record excavation volumes, advance rates, jack pressures, and other parameters to guide a "blind" tunneling operation. Computers controlling the concrete batch plants mentioned previously also automatically record production and keep track of their stockpiles of cement and aggregates. A new and promising field application is monitoring grouting quality and production on a dam foundation (8,26). Factory-like production operations, such as pre-cast concrete plants, are also seeing increasing use of automated monitoring of production. For most projects, however, there is no automated monitoring. Production rates are obtained manually, if at all, and often with questionable accuracy. The problem can be especially difficult in labor-intensive operations. The potential for automation is great, however, and, with improved information, more efficient planning and management of the field operations, should come.

Recording and Processing.—Once operations data is collected, there are many purposes for which it can be used. Selected real-time data acquisition technologies could be interfaced to microcomputer-based software for automatic collection, storage, retrieval, preprocessing, statistical classification and conversion of collected data for analysis, design, and control decision-making. The construction industry already has some experience with time-lapse and videotape cameras recording data on the logical relationships between, and the cycle times of, the various elements in an operation for qualitative evaluation and even for quantitative studies, such as the development of computer-based simulation models (10,15,16,31,35). The film or tape recording technologies are indirect, and have obvious disadvantages like time delay and semi-manual transcription for building manual or computer data files. They and related statistical packages nevertheless provide valuable experience in processing the data once it is obtained. Of particular interest is designing and testing interface software to integrate the raw data collected by electronic devices monitoring real-time physical systems and some of the powerful standard commercial software packages available for microcomputers (e.g., database systems and spread sheets).

Automated Process Control and Robotics

The next paragraphs briefly review the following main areas that relate most closely to automated process control and robotics: (1) On-site automated process control for fixed plants; (2) partial or full automation of mobile equipment; (3) fixed-based or dimensionally constrained manipulators; (4) mobile robots and androids; and (5) sensing and communications technologies.

On-Site Automated Plant Control.—The most progress to date in automation for construction has been made in the control of temporary on-site plants for batching concrete, bending reinforcing steel, and making pre-cast concrete elements. For example, in batch plants for higher volume, high-quality concrete production, such as those for nuclear power stations, a computer controls the selection, transport, weighing, charging and mixing of cement, sand, aggregates, water and admixtures for a batch that meets specified design criteria for a specific structural component, and simultaneously handles administrative reporting for delivery, quality and cost control. To the extent that more construction processes and components can be redesigned for prefabrication in plant-type facilities, whether on-site or off-site, a larger fraction of construction processes can benefit from automated process control of this type.

Automation of Mobile Equipment.—Most major construction equipment manufacturers are experimenting with and even producing some machines that include on-board microprocessors for monitoring performance, maximizing engine power and fuel economy, optimizing gear shifts, keeping loads within safe tolerances, etc. These applications are beneficial, but fairly limited relative to the real potential for the partial or fully automated control of machines as whole units in the overall production process.

More dramatic is the application of automated excavation grade control using laser surveying equipment (see several brochures on laser-controlled excavation and grading, printed by Spectra-Physics, Inc., of Mountain View, California) combined with electro-hydraulic feedback control systems mounted on bulldozers, motor graders, scrapers, etc. In the 1970s, some government agencies and construction contractors helped pioneer these applications of partial automation (46,47). In applications such as highway grading, constructing large parking lots, and canals, these techniques have reduced costs in some cases by over 80% and improved quality (e.g., achieving subgrade thickness tolerances of 2% versus 10–20% otherwise achieved on normal work). They also permit the substitution of lower-costing machines (e.g., small bulldozers for

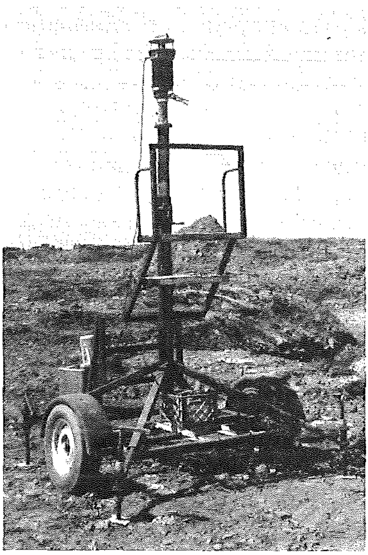

FIG. 3.—Laser Transmitter for Construction Excavation Control

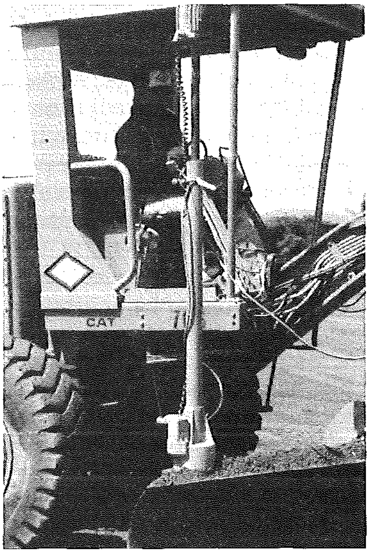

FIG. 4.—Motor Grader with Laser Receiver Mounted on Blade for Automatic Grade Control

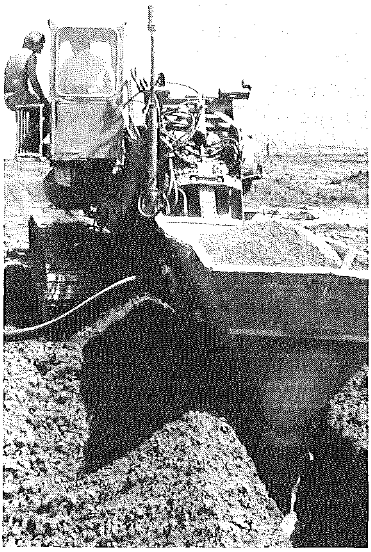

FIG. 5.—Trench Excavator/Pipelayer with Laser Receiver Mounted on Boom for Automatic Elevation Control

motorgraders) and lower-skilled operators, while giving quality improvements. Fig. 3 shows a typical laser transmitter that might guide a motorgrader like that shown in Fig. 4 or a trencher, such as that in Fig. 5. In Figs. 4 and 5, note the laser receivers mounted on a post connected to the blade and excavation boom, respectively. Japan's Komatsu Tractor Company has also done related work in remote-controlled amphibious and submersible bulldozers for work in coastal areas and hazardous environments (2) (see also brochures on amphibious, underwater and remote-controlled bulldozer applications, printed by Komatsu, Ltd., of Tokyo, Japan). Also in Japan, full-face tunneling machines that incorporate a variety of sensing and control mechanisms to optimize tunnel excavation are being implemented (42).

The next step, moving to more fully programmed automation, seems

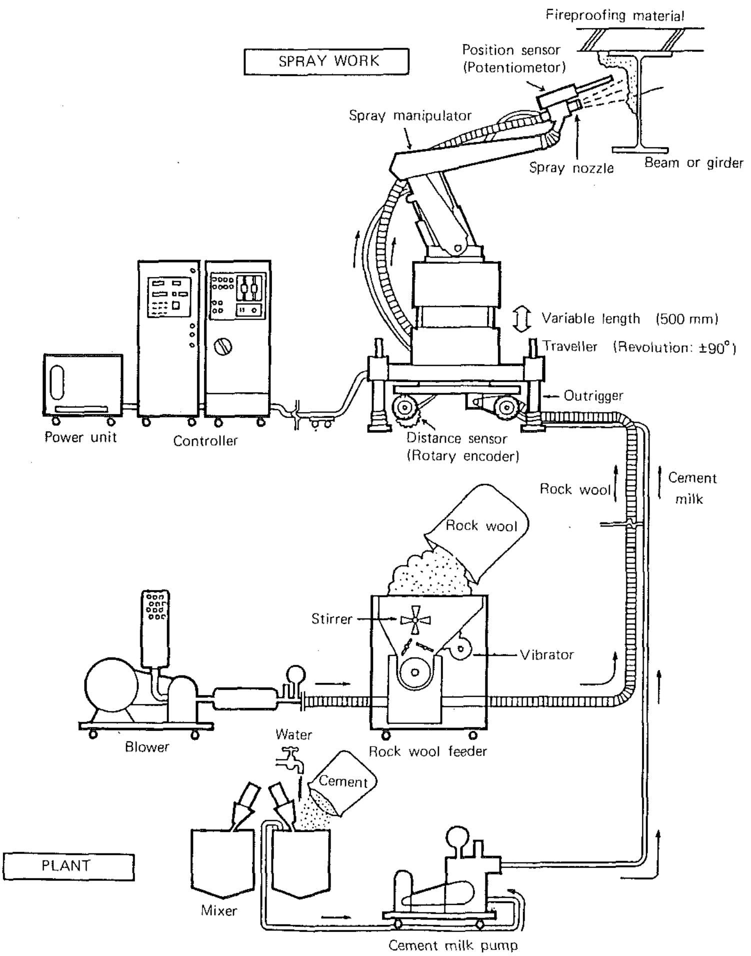

FIG. 6.—Schematic of Equipment for Fireproofing Spraying Robot (Courtesy of Shimizu Construction Company)

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obvious but is much more difficult. At this stage, the machines in effect become robots with some limited programmed intelligence for self-guidance and control over complex routes and surfaces, making decisions on what to do about obstacles, and responding (if only to stop) to unanticipated changes. Researchers at Carnegie-Mellon University have proposed this type of automation, and have generated considerable interest (21,40). The automation of independent machines needs much more research before it becomes safe and practical, but the potential is there.

Spatially-Constrained Manipulators.—Much publicity about robotics in manufacturing industries currently centers on multi-jointed robot arm and hand mechanisms attached to a fixed base or platform, such as a gantry, that covers a clearly defined and limited area. With such a well-prescribed three-dimensional frame of reference, they can be programmed for operations requiring high precision.

Although the construction environment is often loosely constrained and frequently reconfigured, there is still considerable potential for this type of automation. The processes can be redesigned to fit the tools, and the tools can evolve to more flexibly handle a wider variety of processes. Carnegie-Mellon University researchers have experimented with such a robot arm for unit-masonry construction (21). Japan's Shimizu Construction Company has mounted such an arm on a mobile platform

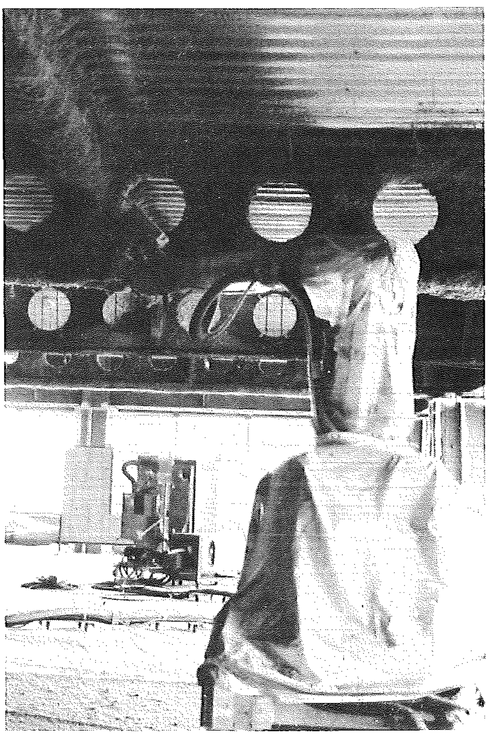

FIG. 7.—Shimizu Fireproofing Robot Spraying Structural Steel in a Building (Courtesy of Shimizu Construction Company)

and is using it to apply sprayed insulation in building construction (18,49,50). Fig. 6 is a schematic of the equipment used with Shimizu's robot. A photograph of the robot at work is shown in Fig. 7. In Finland, a very large robot arm has been used for harvesting trees for wood pulp (24). Other possible applications of such robots are in tunnels where operations (e.g., liner erection) are highly repetitive and fit into well-defined geometric constraints.

Mobile Robots and Androids.—Apart from Shimizu's platform-mounted robot arm mentioned in the foregoing, few attempts have been made to develop and apply mobile, walking-type robots and androids, even in manufacturing, let alone construction. However, owing to the nature of project sites, such devices might have even greater potential in construction than in plant-based manufacturing. A number of possibilities have been explored, including a walking spider-like robot to assist in the cleanup at the Three Mile Island nuclear plant, others for the assembly of space platforms and work on other planets, and the Odetics, Inc., ODEX-I, a promising six-legged robot with a high power-to-weight ratio (6,38) (see Fig. 8). The ODEX-I weighs 370 lb, can walk at a fast pace, and can lift 900 lb at its center point. However, there is no real prototype yet for a general-purpose robot flexible enough to be a general utility tool on field projects. This is an attractive area for research.

Sensing and Communications Technologies.—For years various kinds of instruments have been installed during or ahead of construction operations for technical or safety reasons. Particularly good examples are geotechnical and structural instruments for monitoring tunnel and foun-

FIG. 8.—The ODEX-I Experimental Robot (Courtesy of Odetics, Inc.)

dation excavations. A new and promising application is monitoring grouting operations for a dam foundation (8,26). Furthermore, the electronic revolution has brought rapid advances in surveying equipment that measures distances, angles and volumes. Mobile radio communications have also been involved in construction projects, at least since the 1940s, not only among project engineers and supervisors, but for foremen directing equipment operators, operators calling for fuel or repair assistance, signal men talking to crane operators, etc. In other words, there is already considerable experience with equipment and technologies that could support machine data acquisition and control functions. Little has been done, however, to take advantage of the existing infrastructure for automated process control purposes.

In summary, remote field project-oriented industries like construction have only taken a few, loosely related steps toward automated data acquisition, process control and robotics for field operations. Initially, much can be learned from aerospace research and plant-based manufacturing industries, but in the long run, the challenges and potential rewards are even greater in large-scale field operations.

Potential Applications

Proceeding from the review of the state of the art and the selected examples that have been presented, this section will provide criteria and suggest categories for a more general classification of potential applications of automation in construction.

Understanding and Classifying Potential Applications

In order for automated real-time data acquisition, process control and robotics to begin having a greater impact in construction, it will be necessary to acquire a sound understanding of current and projected technological developments in several discipline areas. The development of a useful classification system would help researchers define appropriate topics and objectives, and guide industry and government in developing effective, coordinated long-term programs of research. Possible general parameters for classifications include the engineering and scientific disciplines needed for further research; their potential areas for application on various capital- and labor-intensive large-scale remote field operations; their present and potential state of advancement (i.e., conceptual, basic research, applied research, development needing only technology transfer, commercial product, etc.); and their likely application areas in field operations (e.g., fully or partially automating present fixed and mobile production equipment, new design approaches suitable for process automation, development of suitable robots and androids).

Potential Applications of Automated Data Acquisition

The types of data that could be considered for automated real-time monitoring and collection include, but need not be limited to:

1. Engineering parameters during construction (such as soil displacement toward a foundation or tunnel excavation; alignment and dimen-

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sional tolerances for structural members; subgrade thickness; and construction live and dead loads on partially completed structures).

2. Quality control monitoring and correction (such as continuous weld quality monitoring; soil compaction; concrete composition and strength; bolt tightness; structural member alignment and deflection; water and air quality; and safety standards). Most quality control procedures produce after-the-fact rejection, with consequential delays, interruptions and expensive rework. Immediate feedback would enable remedial action to be taken while production was under way, and thus minimize the consequences of defects.

3. Production rates and quantities, with measures of associated resource consumption and productivity. Most such data is collected now through manual measurement (surveying) techniques and through administrative procedures like labor and equipment time cards. The former can be too expensive to justify the detailed collection of quantities, and the latter (administrative procedures) are notoriously vulnerable to delays, inaccurate recording and even deliberate falsification.

Potential Applications of Automated Process Control and Robotics

Types of automated process control and robotics applications and technologies that could be considered include, but need not be limited to:

1. On-site automated process control for fixed plants, such as concrete batch plants, reinforcing bar cutting and bending, pipe fabrication, carpentry shops, pre-cast concrete element fabrication, and aggregate crushing and screening plants. This type of application would be the most similar to factory automation, and the main focus would be on adaptations for rapid and economical set-up and take-down (e.g., design considerations for portable plants), a high-turnover and often inadequately trained labor force, provisions for severe environmental conditions, and adaptability to a frequently changing product mix. Considerable progress has already been made by industry in some of these areas.

2. Partial or full automation of mobile construction equipment, including trucks ranging from light utility vehicles to large off-highway haulers; excavating and grading equipment such as scrapers, loaders, shovels, compactors and graders; materials hoisting equipment such as cranes and forklifts; and a wide range of specialty equipment such as paving machines, tunnel boring machines, construction railways, cableways and pipelayers. There has been some progress in a few of these, but compared to category 1 in the foregoing, this application has barely been explored for real-time programmed control, let alone anything approaching robotics.

3. Fixed-based or dimensionally constrained manipulators (sometimes called robot arm manipulators) (5,12,30). These are among the basic ingredients of factory automation, and have obvious applications in areas such as category 1 in the foregoing. But what could be done by relocating such manipulators into traditional field positions? The scope and

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economic potential for these and other possible manipulator applications is great.

4. Mobile robots and androids (6,38,39,48), including those with wheel, track-type and walking transporters. Although such robots often contain one or more manipulating arms like their fixed-base counterparts, they are distinguished by a high degree of mobility, normally unconstrained by tracks, guidewires or other fixed references; they have a wider variety of sensors (sonic, light, touch, temperature, etc.) to cope with changing and less predictable environments; they are often battery powered to move without external power sources; and they typically have more on-board computer power to allow a greater measure of independent programmed analyses of and responses to their environment and tasks. Androids, robot devices that attempt to approximate the physical form and some functions of humans, are included so that the term "robotics" can apply to a wider range of mobile devices, without regard to their physical shape or functionality.

Technologies for Research and Development

To a large extent, construction can get a head start in automated data acquisition, process control and robotics by assimilating and projecting current and future scientific and engineering research in numerous areas, and by focusing the most promising technologies on the needs of project operations. However, concurrent experimental laboratory efforts are also important for several reasons. First, they will provide hands-on experience with some of the key technologies. Second, they will provide the means to implement and test technologies in configurations that might model—on a smaller scale and in a simplified environment—situations more typical of field operations, and that have not been adequately considered in factory applications. Technologies that might be explored, via experimental research, for their suitability in automated process control and robotics could include, but need not be limited to:

1. Microprocessor-based sensors for direct installation on structures under construction and on production equipment for monitoring and control (e.g., strain gauges, load cells, displacement counters, etc.), including the recording and analysis of data from such instruments (3,23,27,28,34).
2. Remote sensor technologies such as electronic ranging and detection, sonic and ultrasonic detection and measurement, touch sensors, and light sensors. A major application of these would be to keep track of moving vehicles.
3. Microcomputer-based process control of plant-type operations, including both analog and digital input and output for switching and manipulation (17,19,22,25).
4. Open-loop feedback control systems, including microcomputer-based sensors mounted on vehicles, where the mobile device or robot needs communications and sensing to maintain its position within the tolerances of its specified tasks.
5. Closed-loop servo mechanisms such as might be employed on fixed-based manipulators, where direct electronic or mechanical feedback pro-

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vides continuous monitoring and precise control of position (7). For example, programmable servo-type robot arm manipulators could provide experience with such mechanisms and further help researchers to explore the possibilities of fixed-based manipulators in on-site production operations.

6. Monitoring and coordinating communications technologies, including analog radio and digital telecommunications (13,41,43), optical (e.g., laser and infrared) data transmissions, and electronic ranging and detection (e.g., radar) between microcomputers and mobile robots or vehicles. A major application would be fixed triangulation stations to keep track of freely moving vehicles.

7. Programming and experimentation with the microcomputer-based coordination of multiple processes to achieve a common task (e.g., the robot supplies materials to the manipulator and helps manipulate parts for fabrication or assembly).

8. Video image pattern recognition and image processing for monitoring operations (e.g., labor-intensive) where it is infeasible to attach electronic or mechanical sensors and for use by robots in materials handling, orientation and navigation (11,28). A promising device is the direct digital array detector, which is like a light-sensitive memory chip.

Identifying Needs for and Barriers to Implementation

In contemplating the future of such technologies, it will be necessary to define, classify, and determine general priorities of needs for and barriers to the implementation of automated data acquisition, process control and robotics in several areas. Categories could include large versus small projects, labor-intensive versus capital-intensive operations, industry sectors (buildings, civil works, process plants, housing), phases and technologies within projects (site work, foundations, structural, piping, electrical, etc.), and types of firms (design-construction, general contractor, specialty contractor, etc.). Where will industry's progress be slowed for not implementing new automation and robotics technologies? Where will costs and schedules be unnecessarily high and quality low?

It will also be important to consider potential industry barriers. In a field like automated process control and robotics, there are certainly some very real social and economic as well as technical barriers that must be identified and overcome or accommodated if research efforts are to succeed eventually in development and implementation (5). Researchers who proceed with such studies should be made aware of these barriers. In brief, the obstacles to technological advances are many in construction, and relate more to institutional problems like craft, company and process fragmentation, risk and liability, codes and standards, than they do to purely technological or economic concerns. Through anticipation and careful planning, the barriers can be overcome, as they have been to some degree in foreign countries and in selected parts of U.S. construction (32).

Identifying Potential Researchers

An important goal of an exploratory study of a promising new area is to stimulate qualified researchers to focus their interests on this field.

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Since many of the technologies and needs being considered will cross discipline boundaries (civil and construction engineering, mechanical engineering, electronics, communications, and computer science), an effort must be made to identify researchers or organizations with the interests and abilities to work in various areas. There are already many university and government researchers in the U.S. construction research communities. Through organizations such as the ASCE Construction Research Council, one could assess interests in doing the type of research described here. What is much less well known, however, is how much interest researchers working at the cutting-edge of the various technological areas being described have in expanding their concepts and goals to the unconstrained, frequently reconfigured and often harsh environment of remote large-scale field operations. In establishing contacts with such researchers to learn about their technologies, one should simultaneously probe their interests in and capabilities for this type of research.

Conclusion

Efforts to define and stimulate interest in a broad program of research in this area could have a major impact on the technology and productivity of the construction industry. Construction has slowed the U.S. economy as a whole in recent decades, and in the process has handicapped other industries for which it provides capital facilities and raw materials (9,44). Focusing the attention of high-technology researchers on this industry requires a considerable development of mutual understanding, and that in large measure will require initiative from the construction industry.

Not surprisingly, there are also national economic reasons for getting such research under way. For example, in a feature cover story titled "Japan Takes Early Lead in Robotics," the July 21, 1983, issue of *ENR* described cases where robots are already performing economically useful tasks in the field for Japanese construction contractors (18). The research laboratories of major Japanese engineering contractors (32) (laboratories which have few if any counterparts in the U.S.) are making this a high-priority field in their research. 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. This could become one more area of technological advancement that Americans could give up without really trying, but is this wise?

Currently, the U.S. has the lead in related computer technologies, artificial intelligence research and even some robotics technologies. Some of this capability should be focused on what could be its most challenging potential application area: Large-scale field construction. If U.S. robot manufacturers will not take the lead, then perhaps researchers in universities and the construction industry itself can take up the challenge. This paper is intended in part to stimulate such efforts.

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Appendix.—References

1. Albus, J. S., *Brains, Behavior and Robotics,* McGraw-Hill, Inc., New York, N.Y., 1981.
2. Asano, J., *Amphibious Bulldozer Construction Methods,* Komatsu, Ltd., Tokyo, Japan, 1978.
3. Auslander, D. M., and Sagues, P., *Microprocessors for Measurement and Control,* Osborne/McGraw-Hill, Inc., Berkeley, Calif., 1981.
4. "Automated CERL Concrete Quality Monitor (CQM)," Fact Sheet, U.S. Army Construction Engineering Research Laboratory, Champaign, Ill., June, 1980.
5. Ayres, R. U., and Miller, S. V., *Robotics: Applications and Social Implications,* Ballinger Publishing Co., Cambridge, Mass., 1983.
6. Bartholet, T. G., "ODEX-I—A New Class of Mobile Robotics," *Proceedings of the 1984 National Topical Meeting on Robotics and Remote Handling in Hostile Environments,* pp. 261–266.
7. Brady, M., et al., *Robot Motion Planning and Control,* MIT Press, Cambridge, Mass., 1982.
8. "BuRec Grout Monitoring Automated on Utah Dam," *Engineering News-Record,* July 5, 1984, pp. 20 and 25.
9. "More Construction for the Money," Business Roundtable, 200 Park Avenue, New York, N.Y., Jan., 1983.
10. Dorman, W. F., Knott, J. L., and Woodhead, R. W., *CYCLONE-Timelapse Analysis System-Introductory User Manual,* School of Civil Engineering, University of New South Wales, Kensington, New South Wales, Australia, Dec., 1980.
11. Duda, R. O., and Hart, P. E., *Pattern Classification and Scene Analysis,* John Wiley and Sons., Inc., New York, N.Y., 1973.
12. Engelberger, J. F., *Robotics in Practice,* Anacom, New York, N.Y., 1980.
13. Faher, K., *Digital Communications,* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1981.
14. Fenves, S. J., and Rehak, D. R., "Role of Expert Systems in Construction Robotics," *Proceedings of the Workshop Conference on Robotics in Construction,* D. Sangrey, ed., Carnegie-Mellon University, Pittsburgh, Pa., June 17–20, 1984.
15. Halpin, D. W., "CYCLONE: Method for Modeling of Job Site Processes," *Journal of the Construction Division,* ASCE, Vol. 103, No. CO3, Paper 13234, Sept., 1977, pp. 489–499.
16. Halpin, D. W., and Woodhead, R. W., *Design of Construction and Process Operations,* John Wiley and Sons, Inc., New York, N.Y., 1976.
17. Hunter, R. P., *Automated Process Control Systems: Concepts and Hardware,* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1978.
18. "Japan Takes Early Lead in Robotics," *Engineering News-Record,* July 21, 1983, pp. 42, 43 and 45.
19. Katz, P., *Digital Control Using Microprocessors,* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1981.
20. Koo, C. C., *Video Data Processing System (VIP): An Operational Data Acquisition System,* thesis submitted to Stanford University, in Stanford, Calif., in 1984, in partial fulfillment of the requirements for the Degree of Engineer.

21. Kraker, J., and Krizan, W., eds., "Robots Coming to Jobsites," *Engineering News-Record,* Feb. 10, 1983, p. 113.
22. Kuo, B. C., *Automatic Control Systems,* 4th Ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 1982.
23. Malmstadt, H. V., Enke, C. G., and Crouch, S. R., *Electronics and Instrumentation for Scientists,* The Benjamin Cummings Publishing Company, Inc., Menlo Park, Calif., 1981.
24. Manninen, M., "Supervisory Control of Large-Scaled Manipulators in Severe Environments," *Proceedings of the Workshop Conference on Robotics in Construction,* D. Sangrey, ed., Carnegie-Mellon University, Pittsburgh, Pa., June 17–20, 1984.
25. McDonald, A. C., and Lowe, H., *Feedback and Control Systems,* Reston Publishing Co., Reston, Va., 1981.
26. "Micros Step Into Dam Grouting," *Engineering News-Record,* Dec. 15, 1983, p. 31.
27. Norton, H. N., *Sensor and Analyzer Handbook,* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1982.
28. O'Brien, J. B., Knott, J. L., and Woodhead, R. W., "A System for Fully Automated Capture and Analysis of Field Performance Data," *CIB W-65, Proceedings of the 4th International Symposium on Organization and Management of Construction,* Vol. II, Waterloo, Ontario, Canada, 1984, pp. 445–454.
29. Parker, H. W., and Oglesby, C. H., *Methods Improvement for Construction Managers,* McGraw-Hill, Inc., New York, N.Y., 1972.
30. Paul, R. P., *Robot Manipulators: Mathematics, Programming and Control,* MIT Press, Cambridge, Mass., 1982.
31. Paulson, B. C., Jr., "Interactive Graphics for Simulating Construction Operations," *Journal of the Construction Division,* ASCE, Vol. 104, No. CO1, March, 1978, pp. 69–76.
32. Paulson, B. C., Jr., "Research in the Japanese Construction Industry," *Journal of the Construction Division,* ASCE, Vol. 106, No. CO1, March, 1980, pp. 1–16.
33. Paulson, B. C., Jr., "Automated Control and Robotics for Construction," *Small Computers in Construction,* W. C. Moore, ed., ASCE, New York, N.Y., May, 1984, pp. 9–19.
34. Paulson, B. C., Jr., "Exploring the Potential for Automated Real-Time Data Acquisition in Construction," *CIB W-65, Proceedings of the 4th International Symposium on Organization and Management of Construction,* Waterloo, Ontario, Canada, 1984, pp. 455–462.
35. Paulson, B. C., Jr., Douglas, S. A., Kalk, A., Touran, A., and Victor, G. A., "Simulation and Analysis of Construction Operations," *Journal of Technical Topics in Civil Engineering,* ASCE, Vol. 109, No. 2, Aug., 1983, pp. 89–104.
36. "Real-Time Weld Quality Monitor," Fact Sheet, U.S. Army Construction Engineering Research Laboratory, Champaign, Ill., Nov., 1979.
37. "Robot Makers Building-Shy," *Engineering News-Record,* April 28, 1983, pp. 30 and 32.
38. Russell, M., Jr., "Odex I: The First Functionoid," *Robotics Age,* Vol. 5, No. 5, Sept./Oct., 1983, pp. 12, 14–18.
39. Safford, E. L., *Handbook of Advanced Robotics,* Tab Books, Blue Ridge Summit, Pa., 1982.
40. Sangrey, D., ed., *Proceedings of the Workshop Conference on Robotics in Construction,* Carnegie-Mellon University, Pittsburgh, Pa., June 17–20, 1984.
41. Shanmugam, K. S., *Digital and Analog Communications Systems,* Wiley, Inc., New York, N.Y., 1979.
42. Shimomura, Y., and Sonoda, T., "Tunneling by Robots: Shield Driving Automatic Control System," *Proceedings of the Workshop Conference on Robotics in Construction,* D. Sangrey, ed., Carnegie-Mellon University, Pittsburgh, Pa., June 17–20, 1984.
43. Sinnema, W., *Digital, Analog and Data Communication,* Reston Publishing Co., Reston, Va., 1982.

44. "Technological Progress in the Construction Industry," *Report B-2*, Business Roundtable, 200 Park Avenue, New York, N.Y., Aug., 1982.
45. Touran, A., *Construction Operations Data Acquisition and Processing Via Time-Lapse Photography Interfaced to a Minicomputer*, dissertation submitted to Stanford University, in Stanford, Calif., in 1980, in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.
46. Ward, C. J., "Automatic and Adaptive Controls for Construction Equipment," *Paper 750765*, Society of Automotive Engineers Off-Highway Vehicle Meeting, Milwaukee, Wisc., Sept. 8–11, 1975.
47. Ward, C. J., "Hydraulic Control Designs for Retrofitting to Mobile Equipment, *Mobile Hydraulic Design Symposium*, Paper 43, May 13–15, 1980.
48. Weinstein, M. B., *Android Design*, Hayden Book Co., Inc., Rochelle Park, N.J., 1981.
49. Yoshida, T., Ueno, T., Nonaka, M., and Yamazaki, S., "Development of a Spray Robot for Fireproof Cover Work," *Proceedings of the Workshop Conference on Robotics in Construction*, D. Sangrey, ed., Carnegie-Mellon University, Pittsburgh, Pa., June 17–20, 1984.
50. Yoshida, T., Ueno, T., Nonaka, M., and Yamazaki, S., "Development of Spray Robot for Fireproof Cover Work," Research Institute, Shimizu Construction Co., Ltd., Tokyo, Japan.