Construction Automation and Robotics—Pathway to Implementation

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Abstract: Research in construction automation and robotics has increased in popularity over the past few years. Although interest is high in the research and education communities, sustaining robust programs is difficult due to the diverse interests of constituents associated with the research and development process. The premise of this paper is that there is a need to develop and maintain strong construction automation and robotics programs in the United States. One way to assist in this goal is to address the concerns of the constituencies of research and development by focusing on a process leading to implementation. The interests of the constituents of the research and development process are examined, a process leading to implementation is presented, and results from a recently completed research project are presented as an example of the process. It is concluded that a systematic approach such as the one presented will enhance the success of construction automation and robotics programs as well as lead to faster adoption of advanced technologies for field applications.

INTRODUCTION

There is growing interest in construction automation and robotics research as evidenced by relatively new initiatives in several civil engineering departments (e.g., University of California, Berkeley; North Carolina State University; and Texas A&M University); the Conference and Exposition on Robotics for Challenging Environments (held with the Fourth International Conference on Engineering, Construction, and Operations in Space, February 26–March 3, 1994, in Albuquerque, N.M.); the annual International Symposium on Automation and Robotics in Construction; the International Journal on Construction Automation and Robotics; and the creation of the ASCE Aerospace Division's Committee on Field Sensing and Robotics in Civil Engineering.

To date, however, few robotic applications are in actual field use, and implementation of both academic and commercial computerized (construction engineering and management systems in the industry has been rather slow (Farid 1993). Additionally, "there is a surprising lack of research and development of partially automated and autonomous road construction and maintenance equipment" (Skibniewski and Hendrickson 1990). Paulson (1985) states, "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-controlled machines from overseas." Another hindrance to the advancement of construction automation and robotics is the fact that "the construction industry, in general, has been traditionally conservative in accepting new approaches" (Kangari and Halpin 1989). Also, "construction research is funded at a level much less than 1% of gross sales, whereas other industries' funding levels are in the range of 3% or more" (Tucker 1988). There is a need, therefore, to nurture the development of successful research and development programs in construction automation and robotics in the United States.

The writers believe that one obstacle such programs face is the diversity and concerns of the constituencies involved in the research and development process. The objective of this paper is to present a systematic process for conducting research in construction automation and robotics, focusing on field implementation. The paper examines how this emphasis can address the concerns of constituencies of construction automation and robotics research. The procedure followed in a recently completed project and results are presented as an example.

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CONSTITUENCIES OF CONSTRUCTION AUTOMATION AND ROBOTICS RESEARCH

Before discussing how the goal of implementation addresses the concerns of the various constituencies involved in research and development, one must first examine the taxonomy of those constituencies. The writers propose that the primary constituencies involved in this arena are research program managers, end users, advanced technology sources, and construction engineering and management researchers.

Research program managers usually wish to fund a project to solve a specific problem, assist in advancing research and education capabilities, or both. These managers also view dissemination of results in the form of products and publications and technology transfer as important issues. While some managers prefer to support only basic research, others wish to see practical applications implemented in the field.

End users of any products of the research and development effort wish to have devices that are practical and easy to use, and that improve performance in some manner—for example, in increased safety or higher productivity. Low maintenance and operator skill requirements are also important.

There are numerous advanced technology sources such as university laboratories, private laboratories, and federally supported laboratories. The U.S. federal government has invested heavily in advanced technology research for military, energy, and space applications. With the downsizing of the military complex, there is an emphasis in transferring this advanced technology to the civilian sector (Lynch 1993). Many federal technology sources, therefore, have a vested interest in using existing technology for civilian applications. Private technology sources are typically influenced by the profit motive.

Civil engineering researchers or construction engineering and management researchers are interested in challenging and rewarding work. They wish to make a contribution, gain the respect of their peers, participate in a vigorous research program, and be accepted as valuable members of the educational and research community.

ROLE OF CONSTRUCTION ENGINEERING AND MANAGEMENT RESEARCHERS

The writers believe that the role of construction engineering and management researchers in automation and robotics may best be described in terms of the four overlapping elements of scholarship as presented by Boyer (1990): discovery, integration, application, and teaching. One is tempted to view the scholarships of discovery, integration, and application as if they should occur in the sequence as presented. Boyer states, however:

> The scholarship of application, as we define it here, is not a one-way street. Indeed, the term itself may be misleading if it suggests that knowledge is first "discovered" and then "applied." The process we have in mind is far more dynamic. New intellectual understandings can arise out of the very act of application—whether in medical diagnosis, serving clients in psychotherapy, shaping public policy, creating and architectural design, or working with the public schools. In activities such as these, theory and practice vitally interact, and one renews the other.

The writers believe that an emphasis on implementation (or application) will, by necessity, involve discovery and integration elements. Implementation will serve as a framework within which the other elements can be directed and facilitate faster technology transfer into field operations. This process may be described as a problem-to-solution approach as opposed to a solution-to-problem approach. Problem identification and thorough examination should come first, followed by the search for advanced technological solutions. The approach, executed properly, will provide positive elements for all constituents.

For research program managers, a particular research project may focus on a specific problem. Such a focus will encourage potential end users that the process has high potential for resulting in a practical, useful product. Technology sources will benefit from the use of their existing technologies that must be enhanced and improved for unexpected purposes.

Construction engineering and management researchers play the role of integrators. They must not only assume the role of technology and systems integrators but also serve as integrators of the constituents to the research and development process—research program managers, advanced technology providers, and end users. They should strive to leverage knowledge and resources as well as ensure that each constituent's concerns are addressed—basic research for some research program managers and applied research for others, for example. To accomplish these goals, some systematic process leading to implementation should be followed.

SYSTEMATIC PROCESS LEADING TO IMPLEMENTATION

Let the Venn diagram depicted in Fig. 1 represent the set of all problems that may benefit from the use of advanced technology. The first major challenge in the process is to identify as

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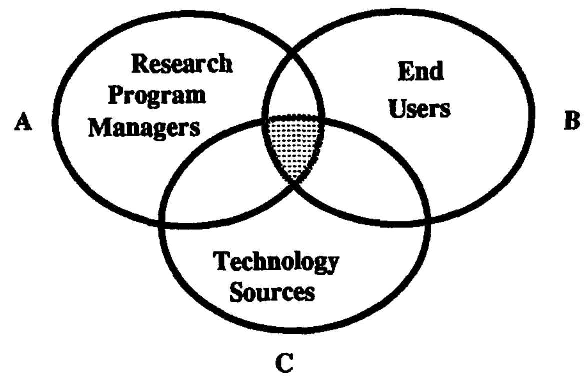

FIG. 1. Venn Diagram of All Possible Problems

many potential problems as possible. Phase 1 of the process, therefore, is problem identification. A very broad net should be cast to identify many potential problems. Interviews and brainstorming sessions with experts in the field are necessary. In total-quality-management terms, this may be considered getting close to the customer to identify the customer's needs.

The second major challenge is to identify those problems that are common to all three groups as indicated by the shaded area in the figure. Let circle A represent problems deemed important by research program managers; circle B, problems deemed important by end users; and circle C, problems for which technology is available to solve the problems or improve performance in some manner. Phase 2 of the process is subjective in that one must build consensus of what problems should be investigated. Once a preliminary set of problems are identified for investigation, phase 2 is completed by extensive literature reviews and interviews with experts to determine initial feasibility. Problems that are determined to lie within the shaded area of Fig. 1 can then be proposed for further research in phase 3.

Phase 3, the objective filter phase, consists of a conceptual design or designs of the pathfinder plus technical and economic feasibility studies. Conceptual designs must exist before performance parameters can be estimated and feasibility studies accomplished. This phase is quantitative and includes technological and economical risk analysis.

Phase 4, the pathfinder development and testing phase, consists of designing and building a laboratory test platform where candidate technologies can be compared. This phase is where technology options are investigated, for incorporation into the prototype, and performance estimates from the previous phase are adjusted to experimental results.

Phase 5, the prototype development and testing phase, consists of building and testing the prototype device. Lessons learned from the pathfinder phase are incorporated into the prototype. Field testing is conducted to verify performance measures.

Applications that successfully pass each of the previous phases are then ready for design enhancements and manufacturing. Training of field personnel and field implementation can then be accomplished. This phase is typically beyond the scope of academic research.

The overall process can be viewed as a filtering process where each successive phase is more rigorous than the previous and eliminates some applications from further consideration. Each successive phase also requires more resources to accomplish. One goal of the process, therefore, is to reduce the cost and risk associated with technology transfer and applications development. This represents an efficient method of development because the majority of available resources can be expended on the more promising applications while unpromising applications can be eliminated without investing substantial effort and resources. The phases of the process are as follows:

1. Identification of potential applications
2. Subjective filters (select mutually important applications)
3. Objective filters (conceptual designs and economic feasibility studies)
4. Pathfinder development and laboratory testing
5. Prototype development and field testing
6. Manufacturing, training, and field implementation

All phases of the process are important. The writers believe, however, that phases 1, 2, and 4 are many times overlooked or receive less attention than deserved. Phases 1 and 2 are important to identify problems and build consensus. Phase 4, the pathfinder phase, is important because the word *prototype* implies a fully functional device that is easily demonstrable. Some observers of a pathfinder device that is mistakenly called a prototype may become disillusioned because the device does not work as expected or promised. The writers use the term *pathfinder* as referring to a partially functional laboratory device used for experimentation. The term *prototype* should be used only on fully functional and field-demonstrable devices.

The balance of this paper presents the results of a recently completed research project as an example of the first two phases of the process. Conclusions include project-related conclusions and process-related conclusions.

EXAMPLE PROJECT

A three-month project called "Applications of Robotics and Other Automated Techniques to the Construction, Maintenance, and Inspection of Highway Systems" was conducted for the Texas Department of Transportation (DOT) in 1993 (Boles et al. 1993). The project serves as an example of phases 1 and 2 of the previously discussed research and development process.

One of the fundamental tenets of the effort was that the customer (Texas DOT) is the expert in identifying its own needs. The project was organized, therefore, to include major participation of Texas DOT. A working group of the department's personnel was formed to identify a wide range of potential applications. The working group conducted brainstorming sessions and identified 47 potential problem areas where improvements in performance were deemed desirable. The areas identified are: culvert inspection; storm-sewer inspection; underwater-structure inspection; surveying (in traffic); placement of raised pavement markers; paint striping and dotting for paint lines; placement and retrieval of traffic cones; flagging for traffic control; nondestructive testing of roadways (density measuring and continuous monitoring); mowing and trimming; herbicide placement; building maintenance, repair, and custodial work; building security (indoor and outdoor); sandblasting and repainting of structures; bridge inspection; sandblasting and repairing of concrete median barriers and bridge rails; graffiti removal (aesthetics) on structures; weld and connection inspection (inside of steel boxes); deicing of structures; automation of bridge-icing signs; sign removal, repair, and installation; pavement crack sealing; filling vehicle tank with natural gas; drilled-shaft inspection; street sweepers; equipment operation (compaction rollers); pavement evaluation (nondestructive testing); application of pavement marking tape; illumination and traffic-signal repair; asphalt placement; cable-stay inspection (bridges); temporary sign installation and removal; shadow truck operation; ditch maintenance, road sectioning, and trenching; litter removal and sorting; inventory evaluation of department appurtenances; plant fabrication (nondestructive testing of beam construction); pothole repair and patching; hazardous material investigation; spill investigation and cleanup; material handling; high-load detection and warning; project videotaping (construction photography automation); road-kill removal; on-site weather monitoring; hot-mix plant stack sampling; and traffic-counting–device installation.

A short list of 17 priority items was selected from the long list to narrow the scope of the study; an advisory Committee, consisting of Texas DOT's upper management, convened and selected a working list of seven problem areas that were to be studied during the summer of 1993. These problem areas are: flagging for traffic control; culvert clean-out and inspection; drilled-shaft inspection (and measurement); placement (and retrieval) of traffic cones; nondestructive testing of roadway density during construction; underwater-structure inspection for scour and corrosion; and luminaire and traffic-signal-bulb replacement.

The involvement of Texas DOT's personnel to identify potential applications deemed important to the department was an effective way of selecting problem areas that meet the requirements of circle A in Fig. 1. The brainstorming sessions, therefore, represented phase 1 of the process, while narrowing of the scope of the study by Texas DOT's upper management represented one part of phase 2. The remaining parts of phase 2 included interviews to assess the importance of the seven applications to field forces (user assessments, circle B in Fig. 1) and technology assessments (circle C in Fig. 1). The technology assessments consisted of a literature review and a 50-state telephone survey to identify current and potential methods of accomplishing the seven tasks as well as interviews with advanced technology experts including personnel from Sandia National Laboratories, Albuquerque, N.M.

Technology Assessments

Flagging for Traffic Control

The three operations in which flaggers are most used are the "stop traffic," "get attention," and "avoid obstacle" operations. Flaggers generally use stop/slow paddles, red/orange flags, or lighted red wands to communicate with drivers ("Traffic" 1980).

Some European countries and Japan use electrical/mechanical signaling devices that have not been widely accepted by transportation management in the United States ("Should Portable" 1991). Timed-cycle portable traffic signals are in limited use in the United States (Richards et al. 1981; "Quartz-Timed" 1988; Ullman and Levine 1987). Image-based traffic-measuring systems capable of acquiring real-time traffic-flow rate, distance between cars, traffic volume, and traffic congestion are also in development (Sakai et al. 1990; Kilger 1992). Several studies of

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speed-reducing, "get-attention" flagging operations, however, have indicated that humans have a slight edge over electromechanical devices in getting drivers' attention (Richards et al. 1981; Benekohal and Kastel 1991; Noel et al. 1991).

The standard stop/slow paddle sign is the flagging method of choice in the United States. Two states reported that they use flags only or police to control traffic. One state reported using a mixture of flags and paddles. Several states reported that they are considering using the newer Strategic Highway Research Program (SHRP) paddles with a strobe light that can be activated to attract the motorists' attention.

One state reported using a tripod-mounted paddle that is remotely operated, and another reported using message boards accompanied by dummy flagmen. One state reported using portable traffic signals even in short-term construction situations. Some states reported using portable or semipermanent traffic signals for long-term construction situations. Other states reported using warning signs, portable message boards, portable speed bumps, and arrow boards in addition to human flaggers.

Other alternatives identified by technology experts included a railroad crossing arm and supervised or autonomous "follow-me" vehicles. Laser or microwave anti-collision systems could be used to prevent collisions with equipment or workers crossing the path. The vehicles could be fully autonomous, but for safety reasons teleoperated or supervised autonomous operation is recommended.

Culvert Clean-Out and Inspection

Many robotic systems exist to inspect interiors of pipes and drainage conduits ("Remote Visual" 1990; Steffes et al. 1991), from companies such as PLS International Co., Cleveland, and some work has been done to detect voids around sewers and under offshore pipelines ("Infrared Thermography" 1985; "Nuclear-Sourced" 1992).

Several states reported using video equipment to supplement visual inspection. All other states perform inspections with the unaided eye of an inspector. For manual inspection methods the U.S. Department of Transportation's stand-alone *Culvert Inspection Manual* (1986), supplement to its *Bridge Inspector's Training Manual*, provides procedures for conducting and documenting culvert inspections. A two-part culvert inspection manual for the railroad industry is also available (Uppal 1980).

For small culvert cleaning, high-pressure water-jet systems are in limited use ("Mole" 1987) from Hydro-Services Co., Missouri City, Tex., for example. The main culvert-cleaning technique, however, is manual cleaning sometimes assisted by high-pressure water and vacuum systems.

The main suggestions by technology experts were for a crawler-mounted cleaning system with a scoop/shovel, water jet, rotary pipe cleaner, and a saw to cut up large objects. Snakelike devices were not as popular as the crawlers because of the difficulty of dealing with bends in culverts. There was, however, one interesting suggestion: a chain with one-way scoops. The idea is to oscillate a chain with folding scoops back and forth through the culvert. The back-and-forth motion of the chain ratchets the debris out of the culvert.

Inspection ideas focused on three technologies—optical, sound, and radar. The optical techniques included laser profiling scanners and video cameras. Laser profiling would yield a more quantitative result while the video systems offer a more user-friendly but more qualitative solution. The main disadvantage of all optical techniques is their inability to examine the soil conditions behind the culvert walls. The sound techniques considered were ultrasonics for interior wall inspection and wall tapping techniques for through-the-wall inspections. Ground-penetrating radar, however, was viewed as the first method to investigate, because ground-penetrating radar systems are well developed and commercially available. Audible techniques may also work to determine whether a culvert is full of debris (Crawford 1988).

Drilled-Shaft Inspection and Measurement

Drilled-shaft inspection presents some of the same problems encountered in culvert inspection. Regardless of the shaft diameter, it is considered unsafe for a human inspector to descend into the shaft unless the shaft is cased. For quality inspections, therefore, a vision device is required to "see" the condition of the bottom and the side walls. For vision in air-filled shafts, many video camera systems, such as from PLS, can be used ("Rotating Camera" 1986). Video-equipped diving bells have been used in water-filled holes (Ho 1982).

For slurry-filled shafts, sensors other than video are required. A robotic excavator for slurry-filled foundation excavations that uses ultrasonic sensors to determine the location of the walls and a computer to guide an excavator is under development in Japan (Kikuchi and Miura 1993).

The major inspection technique in the United States is visual, using a mirror and sunlight or other light source. Inspections are performed from the top of the hole or by lowering a man into the hole (11 states) varying by state with some doing both. Some states use video equipment

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to examine the shaft. One state reported using a gamma-ray testing device and cross-hole sonic logging.

The technology experts' opinions are that the main problem with both the camera and mirror system is that the result is qualitative rather than quantitative. To address this issue, a scanning laser to profile the hole was suggested. Similarly, scanning ultrasonics could be used to map the shaft. Both methods would provide good quantitative records of the shaft profile. For slurry-filled holes, sonar was suggested. An array of listening sensors with a single pinger could likely provide an accurate quantitative map of the shaft. Another possibility for the slurry-filled holes is ground-penetrating radar.

Placement and Retrieval of Traffic Cones

With the increasing rate of work-zone accidents, there is more interest in automating some functions to reduce the number of workers exposed to hazardous situations such as placing and retrieving traffic cones ("Work Zone" 1991). One semiautomated cone machine, from ADDCO, St. Paul, Minn., is in limited use in the United States (Zhou 1991), and a fully automated cone placing and retrieving system has been developed in Japan (Sugiyama 1993).

Traffic-cone placement in the United States is performed manually in all but six states, which are experimenting with a semiautomated device. Some states reported the use of modified trucks to make manual placement easier, and one state uses a truck with impact attenuators.

Since semiautomated devices do exist, the technology experts' primary suggestion for placing and retrieving traffic cones is to evaluate current traffic-cone machines. The availability of machines demonstrates that the task is amenable to automation. Part of the effort should be aimed at determining why the machines are not in greater use. The information could be used to modify existing machines or design new ones.

Nondestructive Testing of Roadway Materials during Construction

Current methods of measuring densities (and thicknesses) of concrete and asphalt pavements consist primarily of nuclear devices (Troxler Electronic Laboratories, Research Triangle Park, N.C.). Methods using ground-penetrating radar, falling-weight deflectometers, and spectral analysis of surface waves are also in limited use and being researched (Lytton, personal communication, 1993; Stokoe et al. 1991).

The majority of states use nuclear-density gauges for testing roadway density. Many states supplement nuclear-density gauges testing with core samples. Other states use falling-weight deflectometers to supplement the nuclear testing. Two states report using only falling-weight deflectometers. One state reported using sonic testing, and one state uses cores only.

The technology experts suggested that one alternative method of determining pavement thickness was the use of magnetic technology. Small metal disks could be randomly distributed before laying the pavement. A detector could be used to measure the pavement thickness above each disk. The experts also noted that existing systems, using vibration or radiological emission, appear to be valid techniques and should be evaluated further.

Underwater Structure Inspection for Scour and Corrosion

Inspection methods used currently include manual (vision and touch) and remote sensing (sonar and video) from ORE International, Houston; American Inland Divers, Inc., Houston; Simrad Mesotech Systems Ltd., Port Coquitlan, British Columbia; and Benthos, Inc., North Falmouth, Mass. Ground-penetrating radar has also been developed and used to determine scour damage (Decker 1988). An automatically controlled system with a sonic probe has been developed to determine metal thickness ("Robots" 1985).

All states reported that underwater inspection is performed by divers. Some states use still photography and video equipment to supplement divers' reports. Three states reported using sonar devices to obtain profile data of river beds. Three states use a depth finder from the surface to map the river bed. One state reported that it is pursuing research into sonic and seismic methods as well as ground-penetrating radar.

The technology experts' discussions on underwater-structure inspection focused on two main issues: mobility and inspection techniques. Any method used must overcome problems such as strong water currents, turbid or black water, deep water, marine growth, communications and data recording, and floating debris. Discussions always started with interest in using one of the many commercially available underwater inspection robots. There were two areas of concern with present underwater robots: possible insufficient thrust and black/turbid water operation. Many systems are likely designed for ocean or lake operation where fast currents are not common. A robot would require strong thrusters to operate in the fast-moving, often turbulent waters. Turbid water is a concern because most commercial systems use video cameras for local navigation and operation.

Two ideas were suggested to address mobility concerns: anchors and structure grabbing. Due

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to the large variations in structures, structure grabbing was viewed as difficult but not impossible. For new construction, it was suggested that robot-friendly anchor points could be integrated directly into the structure.

The inspection task suggestions were in two general categories: automation of existing procedures and nondestructive testing methods. The automation suggestions included robotic cleaning of underwater surfaces, acoustic surface imaging, and a robotic test probe to check foundation soil conditions. Other suggestions included ground-penetrating radar, shaker excitation and monitoring, and acoustic response analysis.

Luminaire and Traffic-Signal–Bulb Replacement

No literature was discovered on robotic replacement of traffic-signal bulbs. The importance of this task varies with rural districts generally not interested since they have few bulbs to replace. It is a very important problem in urban districts. The technology experts' opinions on this task were that it is not economically feasible to automate the task with current technology.

User Assessments

Flagging for Traffic Control

Area engineers were receptive to the idea of using portable traffic lights to control traffic flow in areas of construction or maintenance. One area engineer was aware of an experiment using a mannequin; the experiment failed because the mannequin was "kidnapped" within 3 days and never returned. He did not want a mannequinlike device because some citizens would likely damage it. Generally, maintenance personnel did not favor an automated system for flagging. They did not believe they could trust the device as they could a fellow worker.

Culvert Clean-Out and Inspection

Automating culvert inspection was not considered very important. The ability to see through a culvert was, in general, considered adequate. A small robotic device that has a video capability to allow inspection of culverts too small for a man to enter was of some interest and would likely be used if available.

Culvert cleaning was of more importance than inspection. Several area engineers expressed the desire for some type of equipment to allow them to clean culverts. One stated that contractors bid a very high price to clean existing culverts. Another engineer stated that only 15% of the culverts in his area were large enough to allow a man to enter them to clean them out manually.

Drilled-Shaft Inspection and Measurement

Drilled-shaft inspection is typically performed by engineering staff. The current visual examination technique, which uses a mirror to shine sunlight down the hole, was considered adequate by many field personnel contacted. Some interest in a portable light with or without a video camera was exhibited. Some management and design personnel, however, are concerned that better inspection is needed, especially for slurry holes.

Placement and Retrieval of Traffic Cones

Interest in an automated traffic-cone system varied with the level of traffic on the roads. Rural areas had no interest because they could set cones in periods of low traffic volume. Maintenance personnel in high traffic areas generally do not like setting traffic cones manually from a truck or trailer because of the potential for being struck by passing vehicles. Interest in an automated system is high in these areas.

Nondestructive Testing of Roadway Materials during Construction

This problem evolved into two separate issues: density of subbase, base materials, and asphalt density; and thickness of concrete and asphalt pavements. Existing nuclear testing is considered adequate by most field personnel for measuring the density of base materials. Higher coverage (profile data information) and less time-consuming methods are desired.

The existing method of drilling cores in new concrete pavements to determine thickness is costly and time-consuming. Less costly and higher-coverage methods are needed. The radioactive nuclear-density gauges were thought to be adequate. The only desirable improvements mentioned were a reduction in time required to take a data point and an increase in the frequency of testing. When use of ground-penetrating radar was suggested, the area engineers did not believe the work load of an area would justify the device. They thought it might be useful at the district level.

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Underwater Structure Inspection for Scour and Corrosion

Little interest in underwater inspection techniques existed at the area level, since a specialized team located at the state headquarters did all underwater inspections. The specialized underwater inspection team believed underwater visual inspection could be automated using a remotely controlled submersible. The point was made that the time required to perform an inspection was critical because of the number of bridges requiring inspection. Any automated technique should not require more time to perform an inspection than was currently required using divers, or it would only be used in an exceptional situation (e.g., when the current was too strong for a diver, or debris around the bridge made diving unsafe).

Luminaire and Traffic-Signal–Bulb Replacement

Rural districts had no interest in this application. Urban districts, however, were very interested since they have the responsibility for numerous signals.

PROJECT-RELATED CONCLUSIONS AND RECOMMENDATIONS

Flagging for Traffic Control

This appears to be a human behavioral problem of the motoring public and not necessarily a technology problem of automating existing methods. Portable traffic signals seem to work best. No system, however, is reported as foolproof. While some advancements in improving existing methods can occur, new methods should be explored, such as devices that alert drivers with alarms in their vehicles to supplement current methods. Systems such as this may prove more effective than simply automating certain aspects of existing methods.

Culvert Clean-Out and Inspection

This is a regional problem. It is a serious problem, however, in those regions most affected. Methods using high-pressure water and vacuum are in limited use. These methods are reported to be expensive. Additional research is needed to identify more economical and simple methods cleaning and inspecting culverts.

Drilled-Shaft Inspection

Technology is available to dimensionally map drilled shafts and provide a permanent record of the dimensions. Work should proceed to develop economical and user-friendly inspection devices.

Traffic-Cone Placement and Retrieval

Automation of this activity seems economically feasible only in instances where it represents a major portion of the work day in high-density traffic areas. One is led to question why existing machines are not in higher use. A primary recommended task, therefore, is to determine the reason for the lack of widespread use. This information should be used in the design of newer machines.

Nondestructive Testing of Roadway Materials during Construction

Ground-penetrating–radar technology is ready for implementation for testing thickness of pavements. An implementation study is needed. More research is needed to verify the method for testing densities.

Underwater Structure Inspection for Scour and Corrosion

Some field personnel feel that current inspection methods using human divers are sufficient. Some engineering design and management personnel would like to have more detailed data. Technology is available to increase the fidelity and coverage of the inspections. Remote visual inspection can be performed using existing remotely controlled submersible vehicles except in high-velocity water conditions. Other sensor modalities will likely provide more detailed information, especially in low-visibility situations. Further research is required to determine desired data measurements and methods of obtaining the data from appropriate sensor technologies. Additional research is also required to determine appropriate modifications to existing remotely controlled equipment for use in high-velocity conditions.

Luminaire and Traffic-Signal–Bulb Replacement

The task of robotic replacement of bulbs for traffic lights and highway illumination systems was considered difficult due to the wide variations in equipment and installation. It is believed

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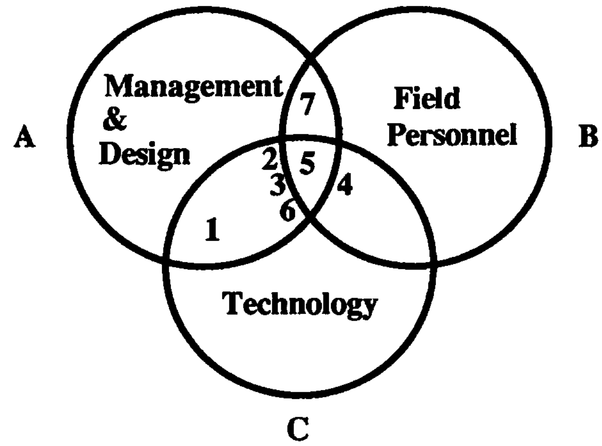

FIG. 2. Results: 1 = Flagging; 2 = Culverts; 3 = Drilled Shafts; 4 = Traffic Cones; 5 = Nondestructive Testing (Density); 6 = Underwater; and 7 = Bulb Replacement

that automating this task is not economically feasible at this point in time. Two alternative suggestions should be researched: moving the light source to a more convenient location, and replacing the traffic-light bulb with an array of high intensity light emitting diodes (LEDs). If the light source can be located in the control box or on the side of the support pole the light can be transmitted to the signal head with optical fibers. An LED has a 100,000-h lifetime. This may represent a life of more than 15 years for a traffic-signal application. For highway illumination, the suggestion was to use light pipes or fiber optics to conduct the light from a base-mounted light source to the desired emission point.

PROCESS-RELATED CONCLUSIONS

The results of the study are represented in Fig. 2. The figure is modified to illustrate Texas DOT's management and design (circle A) and field forces (circle B). It is interesting to note that differences of opinion exist between the field forces and design and management personnel on some applications. As indicated in the figure, management, design, and technology personnel consider flagging, drilled-shaft inspection, and underwater inspection for scour and corrosion as important applications for potential automation. Field operations personnel, however, do not generally view these applications as important. They feel that the way they do these tasks now is sufficient. In cases such as these, management and design personnel can mandate change by requiring more data in the form of physical measurements for inspection methods or safety procedures for flagging operations.

One of the immediate benefits of phase 2 is that it highlights differences of opinion between field and management personnel. Once the source of these differences is identified, appropriate measures can be taken to resolve the differences. Another important result of phase 2 is the discovery of current practices existing in advanced technology applications in other fields. This information is valuable to management in the decision process of pursuing further research.

FINAL NOTE

There is a need to develop successful construction automation and robotics programs in the United States that leverage available resources. To do this, one must address the concerns of various constituencies involved in the research and development process. A systematic process emphasizing implementation is important in achieving this goal. The emphasis on implementation provides some confidence within the user community that practical and useful products will eventually result from their investments. The process also encourages the scholarships of discovery, integration, and teaching since each of these endeavors is dependent and interrelated. The writers believe that a systematic approach, such as the one presented, will enhance the success of construction automation and robotics research and development programs, and lead to faster adoption of advanced technologies for field applications.

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