

Current Status and Key Issues for Construction Automation and Robotics in the USA

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ABSTRACT

Construction automation and robotics research in the United States has been part of the academic and industrial R&D effort since early 1980's. First construction robot and related prototypes were developed in 1982-83. Since then, approx. 10 R&D centers nationwide are engaged in robot hardware development for construction and hazardous waste site applications. However, software development and applications related to automation of structural design, design-construction integration, construction planning and efficient execution of construction tasks are more prevalent in the AEC industry and in leading academic institutions in the U.S. Key issues for future R&D include redesign of construction tasks to take advantage of available advanced technologies, practical application of knowledge based systems in various construction project scenarios, utilization of innovative computational approaches to construction task decision support, and challenges of improved system integration solutions for optimal functionality of construction software and hardware.

1. INTRODUCTION

Construction automation in the United States is a broadly defined planning and technical endeavor which includes two distinct areas:

- 1) Development of computer-based tools for efficient and optimal planning, design, construction and operation of constructed facilities. Of particular importance is the development and practical application of tools for facility design visualization, quantity takeoff and cost estimation, generation of work schedules and job cost reports, design-construction integration, construction task planning, optimal resource management, and design for constructability and maintainability of structures.
- 2) Development of programmable, i.e. robotic hardware for the execution of hazardous construction work tasks, and high volume tasks of simple, repetitive nature. Significant progress has been achieved in heavy equipment navigation, vehicle locomotion systems, autonomous navigation, road maintenance systems, and structural assembly.

Academic R&D centers active in the area of construction automation include Carnegie Mellon University, University of Texas at Austin, North Carolina State University,

University of Florida, Stanford University, University of California at Berkeley, and Purdue University. Industrial centers include engineering construction firms such as Bechtel Corporation, M.W. Kellogg Corporation, Stone & Webster Corporation, and Fluor Daniel Corporation.

2. COMPUTER-BASED ENGINEERING TOOLS

A number of tools have been recently developed to accomplish structural design analysis, construction planning and process setup.

ALPS is Bechtel's Automated Lift Planning System, a graphical crane and rigging simulation tool designed to simulate heavy lifts and to prepare lift plans. This software allows rigging engineers and construction planners to quickly and accurately select cranes and rigging components from pre-defined libraries and interactively design rigging plans. The software system then allows the user to graphically simulate the entire lift sequence, animate the process, and playback the lift either on line or on videotape to communicate the lift plan to other members of the construction team involved. Using ALPS to plan a heavy lift on the construction site allows the lift plan to be developed, documented and communicated in a shorter time and with greater accuracy than using conventional manual methods. The system makes it also possible to change the lift plan quickly, accurately and efficiently. Finally, this software allows engineering personnel, construction superintendents and equipment operators to view, understand and agree upon an animated representation of the lift sequence before actually making the lift. This ensures that all participants are in agreement regarding the lift sequence to be made and know what to expect at the time of the lift. Using this software to simulate, plan and review heavy lifts can provide benefits at all project stages, including project definition, engineering, construction and operations. ALPS runs on all Silicon Graphics color graphics work stations. If running IRIX version 5.3, the newer and faster models are preferable [1].

4D-Planner™ has been developed by Bechtel in response to project visualization, simulation, and communication needs of complex and schedule driven projects involving knowledgeable and active project participants. This planning tool allows the user to combine the 3D CAD model with the project schedule and represent the construction plan graphically. This allows better scenario analyses, quicker understanding of the impact of changes, and improved understanding of the project execution plan by non-technical project participants. 4DP provides a graphical simulation of the work plan that allows early problem identification, including reference detection, and supports scenario analysis or 'what-if' planning. 4D-Planner also facilitates interdisciplinary constructability reviews, and provides a means to graphically represent the results of the planning process. This helps all project participants make faster and better informed planning decisions. As the ALPS software, 4D-Planner runs on all Silicon Graphics computers with IRIX version 5.3. Minimum RAM requirements are 16 MB, although at least 64 MB are recommended. Disk space is a function of the size of model imported and with the size of most standard hard drives is generally more than sufficient [2]. Developments within a similar application domain are ongoing at Stone & Webster Corporation.

The need for computer-aided constructability evaluation is being recognized by several construction research and development centers and engineering design and construction firms. Some firms, such as Fluor Daniel Corporation and M.W. Kellogg Corporation, have devised elaborate computer assisted formal constructability evaluation schemes utilizing their proprietary past project data and designing comprehensive database systems for constructability information retrieval.

Purdue University has recently designed and prototyped the first-of-a-kind knowledge based constructability review and scoring system. Automated Constructability Review

System (ACoRS) sponsored by the Obayashi Corporation from Japan is a prototype system utilizing advanced decision support computing concepts such as machine learning, fuzzy logic enhanced neural networks, and genetic algorithms. ACoRS is intended as an automated feedback tool for structural designers and project managers considering the use of advanced construction technologies including robotics, and consists of three functional modules: Project Design Analysis (PDAM), Technology Effectiveness Analysis (TEAM) and Application Relevance Analysis (AREM). PDAM extracts topological data regarding structural shapes and dimensions from 3D CAD drawings and processes that data using a constructability rule base. Individual constructability rules are generated automatically from past structural assembly records using INLEN - a generic automated knowledge acquisition software. PDAM arrives at the design constructability score representing the level of construction task complexity assuming given structural configuration and dimensions [3]. TEAM evaluates the utility and generic performance factors of a considered construction technology given the characteristics of the structural design at hand. This module also allows sensitivity analysis of technology productivity with changing technology parameters. AREM evaluates application relevance of the considered technology to the performance of construction given specific project job site conditions such as the configuration of access roads, material laydown areas, accessibility of lifting equipment to structural assembly points, layout of temporary facilities, as well as availability and cost of skilled labor [4].

Another software product, sponsored by the Indiana Department of Transportation Joint Highway Research Project at Purdue University, is DICEP - Design Integrated Construction Engineering Platform. DICEP involves application of multimedia/hypermedia computer technology to the compilation and retrieval of constructability lessons learned from past road construction projects [5].

University of Wisconsin-Madison is working on several software projects aimed at automating planning of asphalt compaction in road construction projects and landfill compaction. The first project aims at establishing the framework for an affordable path planning system for the compaction operation using an on-board guidance facility. This facility should integrate an asphalt knowledge based system with an economical sensing system, such as a Global Positioning System and a navigational compass. An algorithm has been developed for an efficient motion plan for the compactor using the results of laboratory and field test data [6]. The second project involves the development of software for the generation of area-covering path plans of an autonomous compactor for the spreading and compaction processes on rough surfaces, the landfill space management, and for determining compaction density [7].

A major software development effort aimed at the automation of building design and design construction integration involves the application of the STEP concept to the standardization of building related product models. This work is coordinated through several research centers including National Institute of Standards and Technology which hosts an Internet 'list-serv' for architecture, engineering and construction related dissemination of STEP related developments (Internet e-mail: step-aec@nist.gov), University of Michigan, and Stanford University.

Rapid development of Internet based electronic communications and the World Wide Web, as well as implementation of 3-D and 4-D visualization software such as VRML is causing the ever increasing implementation of data, voice, graphics and video communications within all parties involved in planning, design, management and execution of construction activities, i.e. clients, architects/engineers, professional construction managers, contractors and subcontractors. Currently, most major engineering construction and design firms have WWW sites and home pages for specific services performed. In addition to transmitting information related to the statement of engineering construction capabilities of a specific

firm, these sites serve as a marketing tool allowing these companies to reach clients worldwide which would otherwise be more difficult to reach.

3. CONSTRUCTION EQUIPMENT AND SUPPORT HARDWARE

Construction robotics are now beyond the initial design and academic discourse stages, as was the case throughout 1980's and early 1990's. A number of American institutions developed prototype hardware for various applications which are now in field testing or initial implementation stages.

Carnegie Mellon University has been the first U.S. institution to become involved in design and prototyping of remotely controlled and autonomous construction robotics, initially mostly for government sponsors such as the U.S. Department of Energy, U.S. Department of Defense, U.S. Bureau of Mines, and National Aeronautical and Space Agency. Carnegie Mellon was the host of the first two International Symposia on Automation and Robotics in Construction in 1984 and 1985, and will host the 14th Symposium in June 1997. A large number of hardware development projects are now on-going at Carnegie Mellon, at the nearby RedZone Robotics, Inc., and at the newly established NASA Robotics Engineering Consortium. These include, among others, two Caterpillar, Inc. sponsored projects; one named 'AutoLoad' aimed at improving productivity and cost of mass excavation, and another focused on development of autonomous navigation for off-road hauling trucks. Others include BOA - an asbestos pipe insulation removal robot, RANGER - a real-time autonomous navigation system for a vehicle with a geometric engine, RASTER - a hazardous waste site investigation robot, NEPTUNE - a storage tank inspection robot, and Rosie - a multipurpose remote work system for nuclear facility decontamination and dismantlement [8]. Regarding the applications of the "automation superhighway" to the teleoperation of construction equipment, initial experiments indicate the feasibility of the Internet for directing robots from any location in the world. For example, anyone in the world with access to the World Wide Web can direct a mobile robot at Carnegie Mellon to be dispatched to one of the possible locations within a defined work space (<http://www.cs.cmu.edu/~Xavier>).

In construction surveying technologies, the Consortium for Advanced Positioning Systems (CAPS) engineered an application of a laser-based positioning device called Odyssey, TM developed by Spatial Positioning Systems, Inc (SPSi). There are two primary components in the system, transmitters and receivers. At least two transmitters are required to provide positioning signals to a receiver. However, any number of receivers can utilize the positioning signals simultaneously. The transmitters can be set up at convenient locations and generally aimed at the work site. Existing benchmarks are used to calibrate the system using any local coordinate system. Each receiver is composed of two lenses mounted on a pole, a processor, a data entry and retrieval system, and a power supply. The two lenses form a line, and the position of the lenses and the known geometry of the pole allow the point of position measurement to be projected to the end of the pole. Since the position of the tip of the pole does not change if the pole is slanted, rotated, turned upside down or sideways, the position of any point that the user touches with the receiver is accurately and "instantly" measured. SPsi system software provides basic functions such as distance between two points, areas, volumes, or angles. However, the integrated site positioning system combines real-time coordinate data from the Odyssey system with CAD design data. The combination of real-time coordinate measurement and CAD representation allows field position and graphical design data to be provided simultaneously to the user. There are a variety of applications of this system for new construction as well as retrofit projects. For example, in facility characterization, the comparison of 'as designed' with 'as built' physical parameters is a large application area in itself. Other applications include industrial

plant outage planning and simulation, modular planning, fabrication and construction, consistent site control during construction, providing plant database baselines, and real time position feedback for autonomous construction equipment and robotics [9].

North Carolina State University is involved in three general areas of construction robotics application: excavation, bridge maintenance, and masonry construction. Hardware and software development is ongoing on the buried utilities detection system (BUDS), intelligent control and real time CAD display for excavation, virtual control of large-scale manipulators, bridge painting, raised pavement marker applicator, and masonry construction [10].

University of Florida is developing an autonomous navigation and teleremote mapping system for heavy construction equipment. Following an earlier retrofit of a John Deere 690 excavator with remote control features and autonomous excavation capabilities, a Caterpillar D7 dozer has been recently automated for remote and autonomous operations, particularly for application to the clearance of mines and obstacles. This application has been commissioned by the U.S. Marine Corps and is performed in cooperation with Wright Laboratory at the Tyndall Air Force Base. A universal tele-remote kit installed on the dozer by OmniTech Robotics, Inc. provides the user with an operator joystick control unit from which he can control all dozer functions, i.e. throttle, steering control, etc. The user is provided with video image to assist with remote operation. The converted dozer includes an onboard vehicle positioning system which can accurately determine the dozer's absolute position and orientation. This data is then communicated to a user interface station where it is graphically displayed to assist the operator in controlling the dozer. In addition, the dozer can be navigated autonomously to a user specified goal position. The vehicle positioning system consists of an inertial navigation system and a Global Positioning System which are integrated by an external Kalman filter based program. The dozer is equipped with cameras which transmit video and audio signals to the vehicle control unit. A VME computer onboard the dozer transmits the calculated vehicle position and orientation to a Silicon Graphics computer in the base station for display for the user. Autonomous navigation is accomplished by calculating the location of a series of intermediate target points along the desired path. The dozer is then controlled by reducing the error between the current heading of the vehicle and the heading to the closest target point along the path. As the dozer approaches to within a specified distance of the target point, the target point is changed to the next one in the list. The onboard computer calculates a desired throttle value in order for the dozer to maintain the specified speed and the ratio of individual track velocities in order for the dozer to head toward the next target point. This information is communicated to the Silicon Graphics computer at the base station where the data is converted to an analog signal and sent to the operator control unit [11]. Robotics excavation research and development is ongoing also at the University of Arizona at Tucson.

Lehigh University is continuing development and application research of its patented ATLSS beam-to-column connections comprising a tapered tenon piece on the steel beam that slips into a mortise guide mounted on the column. The three-dimensional tenon is of conical shape and has two web-framing plates. The conical cavity in the mortise, which is shaped to receive the tenon, has a seat, a seating screw, and flutes. The seating screw provides a physical connection between the tenon and mortise, while the flutes add the tension and flexural resistance of the assembly [12]. With the use of Stewart Platform robotic cranes (RoboCrane developed at the National Institute of Standards and Technology), this connection facilitates the automation of the building structural steel frame assembly process. Lehigh's technology transfer company, Competitive Technologies, Inc. is now forming a consortium of national and international partners to follow a commercialization strategy of this invention to put it into standard construction practice.

The automation needs assessment methodology developed earlier at the University of Texas at Austin has been recently applied to several construction projects, including Taipei Rapid Transit System in Taiwan, evaluation and ranking of automated road maintenance systems in the United States, and the application of advanced enabling technologies to construction tasks in environmental remediation. Several hardware developments started in early 1990's are being improved upon, including a large scale manipulator for piping construction [13], automated road surface maintenance hardware, and computer aided critical lift planning. Also, following the development of an automated vertical surface finishing system, a model has been developed to help contractors determine the feasibility of automating their surface finishing operations. It includes a method to help contractors select an effective combination of mobility system and cleaning process to suit particular surface finishing requirements. In other developments, Sika Robotics Inc.'s telerobotic equipment suite was evaluated for its suitability for spot repair of distressed sewers and compared with conventional open cut method, keyhole trenching using Miller Pipeline Inc.'s Vac-Hoe™ equipment, and with epoxy injection using Amkrete Int'l Inc.'s technology.

4. CONCLUSIONS AND FUTURE ACTIVITIES

Office work automation at American AEC firms has become to a large extent a reality. Most recent developments in the automation of design-construction integration are taking advantage of the existence of the "information superhighway" allowing company professionals to communicate and transfer data instantly not only within their own organization, but also with clients, subcontractors and other parties which may be located worldwide.

Research and development of core technologies for robotics continues to make remarkable progress. In areas closely related to construction as far as robotics are concerned, one business study of the future market importance of field robotics indicates that robotics for agricultural machinery, mining and cargo handling will represent a \$2 billion industry by the year 2006 [14].

Much remains to be accomplished to bring about successful automation of today's construction and related tasks on U.S. job sites. Concerns for short term profits, fierce competition among contractors, and lack of top management commitment to technological change are often cited as primary obstacles to rapid introduction of automation and robotics technology among U.S. construction firms.

To date, primary motivation for the robotization of on-site work was to remove humans from safety and health hazards. Eventually, with shortages of skilled construction labor becoming more acute, the scope of tasks considered for automation will be enlarged to include most of the simple, high volume and repetitive tasks which could be effectively automated. More emphasis in the development of new construction systems will be put on the redesign of traditional work tasks to better match the limited capabilities of automation and robot technologies.

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