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Construction Robotics: A Perspective

Abstract

Construction robotics is an infant discipline whose mature form is not apparent. Despite the many advantages and benefits of introducing robotic technology to the construction work site, progress to date has been circuitous. Needs, prospects, challenges, and goals of construction robotics are presented. They suggest an evolutionary approach to the development of advanced construction machines, building on developments in parallel domains. We speculate that the forms of teleoperated, programmed, and cognitive robots and their hybrids will all be relevant in the long term.

Introduction

Construction synthesizes products by initiating tasks in unstructured environments to accomplish goals that satisfy prespecified designs. Structured environments, like those found in factory settings, do not admit the dynamism and uncertainty attendant with unstructured environments. Active and forceful manipulation of objects in unstructured environments requires much more than current industrial robotics can deliver. To work in a construction site -- say, digging up a gas pipe -- a construction robot must be able to recognize unknowns and respond to unplanned difficulties, such as when an excavated pipe is reburied by a cave-in; it is paramount that the robot sense such events and take contingency actions. Research must be committed to the development of robotic automatons that exhibit the intelligence and strength for work in such hostile and dynamic settings. Needs of the open work site drive the agenda for construction robotics research.

In this paper, we examine the motivations, issues, and prospects for construction robotics. The skeletal agenda for construction robotics research is presented and discussed. We then examine the significance of and make some distinctions between teleoperators, programmed machines, and cognitive robots. And finally, we speculate on the relevance of the broad intersections between robotics and construction, predicting possibilities for this fledgling discipline.

Needs and Prospects

Construction is a ripe, virtually untouched, and inevitable arena for robotic applications. Representing six to ten percent of the United States Gross National Product, construction dwarfs manufacturing and other industries that have successfully embraced simpler, deterministic automation. However, labor efficiency is alarmingly low in construction and the need for improved productivity is evident. Worker time spent idle or doing ineffective work may exceed half the work week [8], and productivity has generally been in decline for two decades. [9] Thus, industry size, economics, existing inefficiencies, and competition motivate the introduction of robotics to construction. [5] Other motivations include quality assurance and the prospect for better control over the construction site of the future. Further, because construction is a hazardous occupation, concerns for health and safety provide additional impetus for robotic implementations.

In addition to all these motives, certain applications are inevitable because of the limitations of man. Although distinguished as a master builder, man is not perfectly suited to construction; machines are often better equipped for many applications. Man, for example, is vulnerable to hostilities such as weather, dust, vacuum, submersion, and cave-ins, and limited by a lack of scale or power for activities such as ceiling reach, pallet lifting, and steel bending. Man is also handicapped by an excess of scale for tasks such as pipe crawling and conductor snaking. Man lacks certain sensing modalities, memory structures, and computational abilities that will allow the robots of the future to precisely sense encased steel beams and columns magnetically, strategize and execute tasks in scaled or measured environments, and optimize automatic material distribution throughout a site. The needs of the construction industry, then, will drive the development of unstructured robotics just as manufacturing and assembly drove structured robotics and hazardous environments drove teleoperation. [13]

Despite evident need and apparent promise, the evolution of construction robotics will be circuitous; growing pains may be especially sharp. Construction, an ancient craft, has been historically slow to embrace new technology. Research investment levels have been -- and remain -- insignificant. No precedents in the industry for development programs of the requisite magnitude exist. Because construction problems are difficult (and hence, worthy challenges), quick fixes or one-shot solutions will be few, running counter to construction's historical insistence on short-term payoff for investment. Obstacles to the growth of construction robotics are compounded by the lack of common ground between the construction industry and the robotics research community. The industry cannot yet visualize a programmatic course of action for integrating the growing robotic technology with its own.

Because construction robotics activity is spare, especially in the US [6, 12], current opportunities for development lie outside the construction mainstream. For the time, it seems that spillovers from related fields (demolition, subsea, space, nuclear, mining, and military) will drive and pace many construction robotics developments. Subsea and space applications, in particular, present unique technical challenges to robots, specialized motivations for construction, and constraints and regulations that discourage the use of human workers. However, the formative integration and drive for construction robotics must ultimately come from the construction industry itself. The inevitability of construction robotics will drive its evolution despite the immediate immaturity and impotence of the field.

Challenges and Goals

Construction objectives require diverse capabilities and system views. The skeletal agenda for construction robotics research, driven by the needs of dynamic, unpredictable, unstructured work sites, is presented here.

- *Perform goal driven tasks whose contingencies defy preplanning.*
  Consider the task of demolishing a sidewalk expecting a composition of standard unreinforced slabs. In the course of excavation, the system discovers that the sidewalk is not only integral to an adjacent foundation, but is also heavily reinforced, defying the effectiveness of the intended light tooling. Cognitive functions must recognize these contingencies and automatically adjust their plans to cope with unexpected conditions in the environment and events in the process.

- *Strategic, tactical, and reflexive paradigms for generic work tasks.*
  Reflexive actions are essential for instantaneous response, but are neither global nor robust. Alternatively, global strategic plans are too slow for self-preservation and coping with contingencies. Tactics cover the middle ground. Construction robots must plan at three distinct levels of abstraction. At the bottom lies the signal and physical level, encompassing sensory data and reflexive action. The intermediate, syntactic, level represents the robot's understanding and action in symbolic form. The highest level includes semantic concepts such as "purpose," "goal," and "mission." These three levels also correspond to degrees of intimacy in man-machine interactions. For autonomous system actions, a human operator need only interact at the semantic level. For supervisory control, the human communicates at the syntactic level, and in teleoperation, interaction takes place on the physical level. [1]

- *Complex, perceptive sensing in random and dynamic environments.*
  A full field of data is necessary to infer significant properties about objects in

the environment. Multiple modes of sensing such as range, vision, magnetics, or temperature may all be necessary for modeling complex phenomena. Sensor fusion is especially important in construction sites where simple modeling does not suffice and where the environment is dynamic.

- *Domain-specific tooling and operating procedures.*

Robots are unable to use conventional tools in the same manner as humans. Robots do not have the same physical forms as humans; specifications such as number of arms, type of grip, dimension, strength, dexterity, and rigidity all suggest different, and perhaps non-conventional, tools for robots. For example, the human finesse in using a hand saw requires floating through dynamic trajectories, controlling forces, and employing tactics against pinching. These procedures are inappropriate for a robot. A power saw, however, is appropriate because it simplifies task planning, reduces complex physics to brutal kinematics, and because the robot is able to supply power to the saw in a usable form. In robotics, things that work well are usually simple, but no matter how simple things are for a human, they are still complex for a robot. The correct choice of tools and procedures is critical because these choices have rippling consequences throughout the system.

- *Extremes of ruggedness, reliability, and intrinsic capability.*

A robot must survive in its environment to accomplish goals on its own. Implicit in the ability to accomplish, though, is the ability to err. Because construction robots must be self-preserving, contingency actions and fault tolerance must be imbued into the system. Little utility would be derived from a robot that fails when a ten micron dirt particle contaminates its servo valve. Further, the robot design must anticipate the extremes and impediments of a work site and incorporate devices and techniques for handling them gracefully.

- *Larger working forces and softer base compliance than typical factory operations.*

Consider heavy construction equipment with pneumatic tires working to topple a utility pole. Forceful grappling with the pole causes significant rocking and pulling in the robot chassis, wheels, and suspension. These distortions invalidate kinematic planning that has proven so useful in factory settings. Stabilizers can be deployed to stiffen the otherwise compliant system, but the stabilizers engage the ground surface, which is itself compliant. For the large forces typically encountered in construction, a consideration of system distortions must be incorporated into the control scheme.

- *Navigation and mobility around the work site.*

Construction tasks have dimensions that exceed the reach of equipment performing them. For example, excavation for a long pipeline proceeds in a wavefront; dig-move cycles are iteratively applied to exhume the pipe. Robots that move must also navigate because motion goals force encounters with other objects in the environment. Mobile robot effectiveness around the unstructured work site is measured, in large part, by the ability to know places and to navigate to them. Rolling, climbing, walking, snaking, and prehensile locomotion will all be important for future construction robots.

- *Protocols for communication among humans, dataservers, hosts, and robot*

> *peers.*
> The introduction of multiple robots to the work site raises additional issues distinct from those for individual machines. Central coordination by a host may be necessary to plan, monitor, and optimize the pursuit of communal construction goals. Mechanisms, protocols, and methods of interaction are necessary for the flow of plans, commands, and information between the host and the robotic construction fleet. Human interaction should also be provided for when operations overwhelm the host or the individual automatons. [14]

Robots for Construction

Robots, in general, fall into three classes, each distinguished by the control procedures available to the robot and its relationship to human supervisors. The first of these classes, *teleoperated robots*, includes machines where all planning, perception, and manipulation is controlled by humans. *Programmed robots*, the second of these classes, perform predictable, invariant tasks according to pre-programmed instructions. *Cognitive robots*, the third class, sense, model, plan, and act to achieve goals without intervention by human supervisors.

A widely accepted definition characterizes a robot as a reprogrammable, multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks. This definition, valid to a point in the factory, excludes the high and low end capabilities of devices that are relevant in unstructured environments, and under emphasizes the importance of mobility and force that are essential in construction. The definition is inadequate in other ways as well. Teleoperated systems, though not necessarily programmable, have proven themselves in unstructured environments. [4] Likewise, cognitive robots with reactive planning capabilities go beyond the classical definition of programmed machines by devising strategies on their own.

Distinctions among teleoperated, programmed, and cognitive robots are not always clear, any more than the identity of "robot" is clear. Even when we talk about construction robots in particular, definitions can be ambiguous. Simply, a construction robot is a robot that constructs, meaning builds, and yet such robots do a lot more; they exhibit flexibility in the roles they play and the equipment they use, and they perform tasks of a complexity that previously required human control. [2]

Whatever their differences, however, it is likely that all three classes of robots and their hybrids will find sustaining relevance. Experiences are too few and it is too soon to resolve the relative importance of these forms or to discount the potential of any form. The Japanese have embraced teleoperators and programmed machines for construction. [7, 10, 16, 17] Perhaps the early American views of construction robotics overestimated the need for sensing, artificial intelligence, and autonomy. We speculate that these cognitive attributes will eventually dominate construction robotics. Nonetheless, teleoperators and programmed machines have both short- and long-term relevance.

Teleoperated Robots

Teleoperation is proven where man does not tread, where demands are superhuman, where tasks are unstructured (by current measure), where liability is high, and where action is inevitable. Besides construction, likely short-term arenas for teleoperated robots include space, sea, nuclear, mining, timbering, and firefighting. Teleoperated machines, servoed in real-time by human operators who close the strategic control loop, amplify the human. Because all perception, planning, high-level control, and liability rest with the human, teleoperation circumvents the stickiest and most difficult issues that face other robot control modes including the liability of passing control between machine and human, and coping with unanticipated scenarios.

Beyond teleoperation's relevance for its own sake, a grasp of teleoperation is essential to the evolution of other robot species. Teleoperated implementations are confronting and eroding away the physical limitations of inanimate hardware. Further, teleoperation is evolving robot forms and bodies suited to unstructured tasks. Teleoperation's man-machine interface is at least a useful straw-man for incubating the host-machine and machine-machine relationships that characterize other branches of robot evolution. The man-machine interface will endure because humans will always need to interact with robots for purposes of conveying goals, exchanging information, and influencing courses of action.

An example of a teleoperated robot is the Ohbayashi-Gumi Concrete Placer. This machine has a four-link, servo-hydraulic arm controlled by a microprocessor for automatic operation. The Concrete Placer rapidly pours concrete into forms. It eliminates heavy, dirty work, prevents displacement of reinforcement bars, and hence, reduces concrete placing labor costs. Another example of a teleoperated robot is the Shimizu Mighty Jack. The Mighty Jack manipulates steel beams and sets them into place more rapidly and safely than conventional techniques. While lifting beams, the manipulator is suspended from a tower crane; while setting beams, the manipulator grasps the tops of columns. The tower crane releases the Mighty Jack and goes about other duties while the manipulator positions the beams (suspended on cables) between the columns. The beams are then fastened to the columns manually. [10]

A downside of teleoperation is that much is lost in translation across this man-machine interface. Robot bodies and senses are not optimal for coupling to man. Similarly, human minds are not optimal for the control of robots because of limitations in input/output bandwidth, memory structures, and numerical processing. The symbiosis of steel, silicon, and software now emerging may ultimately supercede the historical symbiosis of man and steel. The prospect exists for construction automatons to outperform their human counterparts in some ways.

Programmed Robots

Programmed machines are the backbone of manufacturing; preprogramming may be extensible to an important class of construction tasks (mostly on the periphery of the construction mainstream, and mostly unenvisioned and untried at this time). [11, 12] Programming choreographs a ballet via a joystick, software, or both. The dance is played back by rote with branching of the script occurring on cue, with appropriate tools and materials as props in the performance. Machine ballets are only useful for predictable and invariant tasks, limiting the general use of pre-programmed robots for construction.

An example of a programmable machine, the Shimizu Insulation Spray Robot, has three degrees of freedom on its base for traveling around the work site, and six degrees of freedom for its spray manipulator. The robot is given a geometric model of the structure to be sprayed. First the robot dead reckons along the structure. The robot uses a tactile probe to correct the dead-reckoned position and then plays a spray script. The robot moves incrementally along the structure and repeats the reckon-position-spray task. The Insulation Spray Robot applies insulation faster and as accurately as a skilled human worker and isolates the worker from a dirty, uncomfortable environment. Another example of a programmable machine is the Kajima Reinforcing Bar Arranging Robot. Manually placing reinforcing bars is difficult and time consuming; the weight of the bars exceeds 100 kgf. The Bar Arranging Robot can carry twenty bars and place them automatically at prearranged intervals. The Kajima robot reduces labor costs by forty percent and reduces total arranging time by ten percent. [10]

Hybrid forms of teleoperation and programmed machines are becoming increasingly attractive as robots. For example, because factory processes are becoming more sophisticated as they integrate preprogramming and sensing, supervisory controllers and sensory feedback with teach/playback are becoming new research goals. Hybrid, supervisory, and programmable robots are also evolving from the roots of teleoperation in the nuclear service and decommissioning industries. Research implementations are seeking to abstract the syntactic (object) level with cognition deferred to intervention by a human. The Toshiba Decommissioning System has two teleoperated arms with 25 and 100 kg payloads. (The 100 kg payload arm also incorporates force feedback.) The arms are mounted on an inverted base that descends and rotates about a vertical axis. After gross positioning, stabilizers brace against surrounding walls. An alternate mode enables preprogramming and teach/playback with the capability for scaling motion and force between the master and slave. A high-level language is in development to elevate the mechanics of human programming. The human interfaces already use symbolic display and crude monitoring, but have yet to incorporate perceptive sensing, tactical planning, or reflexive response.

Cognitive Robots

Cognitive robots sense, model, plan, and act to achieve working goals. Cognitive robots servo themselves to real-time goals and conditions in the manner of teleoperators but without human controllers; they are their own supervisors. Cognitive robots pursue goals rather than play out scripts; they move toward goals and notions rather than to prescriptions and recipes. Although software driven, they are not programmed in the classical sense. Cognitive robots are perceptive and their actions are interactive; they take action in the face of the vagaries and contingencies of the world. Performance is responsive to the state of the environment and the robot itself.

Not many examples of cognitive robots currently exist and those that do are not very bright by absolute measure. Terregator, a six-wheeled autonomous land vehicle designed for outdoor navigation experiments [3], comes close to the ideal of a cognitive robot with its goal orientations such as "circumnavigate the campus" or "map a mine," but these navigation feats fall a little short of construction's active criterion. REX, a robotic excavator designed to reduce the hazard of exhuming gas pipes [15], is a better example in that "dig up pipes" is a goal requiring forceful interaction and alteration of environment. A REX excavation has the unpredictability and liability that attend a capable free agent in the world.

Future Directions

If automatons eventually prove themselves infeasible for unstructured environments, then our views on what constitutes structure must change. Robots other than teleoperators may be irrevocably synonymous with structure. However, our judgment in this matter should not be too clouded by current measures of structure and machine perception. It is common to mistake or overestimate chaos in a task environment simply because form and understanding are not apparent. There is a great prospect for structuring the apparently unstructured either by discovering structure or by imposing it.

The evolution of construction robots will distill unique attributes for robots with working goals in unstructured environments. New robotic forms will emerge with the capability and the strategic competence to construct, maintain, and demolish. The evolution of construction robotics will no more culminate in a single, ultimate form than did its biological counterpart. Rather, classes of robots will emerge for classes of work within classes of constraints. Even the robot genus/species formed and proven in other application domains remains untested by construction. No doubt most of the forms evolved for other purposes will find relevance somewhere in construction, if only because construction's umbrella is so broad. The discipline of construction robotics is embryonic. Its maturation is inevitable, but its mature form is not apparent. Given the uncertainty of what robotic forms may be relevant to construction, we argue that the field should remain open to all the possible hybrids from teleoperated to autonomous, cognitive robots.

Higher animals construct, and the highest animals construct with diverse tools and resources. Useful construction robots will exhibit unique denominators that imbue the ability and the cognitive goals to build. Vital evolution is served by frequent generations and it is important to push prolific, quality implementations into the world. Natural selection is the valid measure of relevance in evolution, perhaps superceding self and peer evaluation.

The discipline must persevere to distill the unique identity and intellectual content of construction robotics. The uniqueness of construction robotics appears to lie in the cognitive skills and goals that are specific to the synthesis of an end product. Much research and many goals in construction robotics, however, are generic to unstructured robotics, so construction can benefit from parallel developments in related fields. Little applicability would be lost by changing the domain specificity from construction to nuclear, mining, timbering, or military. It seems, though, that construction will be dragged reluctantly to the opportunities of robotics. Nuclear, military, space, and offshore interests are embracing and driving the ideas now. It is essential, though, that construction robotics identify and drive the developments that will distinguish it as a discipline of its own.

While the construction robotics label seems limiting to opportunities and even has regressive connotations in certain technology circles, there is a long-term need to maintain the unique construction robotic research focus. Scientific and industrial bonds are finally forging and the perspectives from ground breaking work are beneficial. New developments in construction robotics are strengthening important ties between civil engineering, manufacturing, mechanical engineering, electrical engineering, computer science, and robotics research.

References

[1] Carbonell, J., Kanade, T., and Whittaker, W., *Robot Work Systems*, Proposal to the Office of Navy Research, The Robotics Institute, Carnegie Mellon University, April 1985.

[2] Everett, LCDR H.R., "Robotics Technology Areas of Needed Research and

Development," White Paper 90G/119, Office of Navy Research, September 1985.

[3] Kanade, T., Thorpe, C., and Whittaker, W., "Autonomous Land Vehicle Project at CMU," *ACM Computer Conference*, February 1986.

[4] Martin, H. and Kuban, D., *Teleoperated Robotics in Hostile Environments*, Dearborn: Robotics International of the Society of Mechanical Engineers, 1985.

[5] Moavenzadeh, F., "Construction's High-Technology Revolution," *Technology Review*, October 1985.

[6] Paulson, B., "Automation of Robots for Construction," *ASCE Journal of Construction Engineering and Management*, Vol. 111, No. 3, September 1985, pp. 190-205.

[7] Sagawa, Y. and Nakahara, Y., "Robots for the Japanese Construction Industry," *IABSE Proceedings*, No. P-86/85, May 1985.

[8] Sanvido, V., "Productivity Improvement Programs in Construction," Technical Report No. 273, The Construction Institute, Stanford University, March 1983.

[9] Skibniewski, M., *Strategy for Engineering and Economic Analysis of Robotics Applications Potential in Selected Construction Work Operations*, Ph.D. Thesis Proposal, Carnegie Mellon University, November 1984.

[10] Suzuki, S., "Construction Robotics in Japan," *Third International Conference on Tall Buildings*, Chicago, 1986.

[11] Warszawski, A., "Application of Robotics to Building Construction," *First International Conference on Robotics in Construction*, Carnegie Mellon University, 1984.

[12] Warszawski, A. and Sangrey, D., "Robotics in Building Construction," *ASCE Journal of Construction Engineering and Management*, Vol. 111, No. 3, September 1985.

[13] Whittaker, W., "Cognitive Robots for Construction," *Annual Research Review*, The Robotics Institute, Carnegie Mellon University, 1986.

[14] Whittaker, W. and Bandari, E., "A Framework for Integrating Multiple Construction Robots," *International Joint Conference on CAD and Robotics in Architecture and Construction*, Marseilles, France, June 1986.

[15] Whittaker, W. and Motazed, B., "Evolution of a Robotic Excavator," *International Joint Conference on CAD and Robotics in Architecture and Construction*, Marseilles, France, June 1986.

[16] Yamada, B., "Development of Robots for General Construction and Related Problems," *Research Conference*, Material and Construction Committee, Architectural Institute of Japan, October 1984.

[17] Yoshida, T. and Ueno, T., "Development of a Spray Robot for Fireproof Treatment," *Shimizu Technical Research Bulletin*, No. 4, March 1985.

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