Ongoing Developments in Advanced Robotics in the USA

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Introduction

Over the many years, developments in advanced robotics in the U.S. have been driven by the needs of hazardous work environments, including those related to construction. However, as reported in the previous ISARC proceedings, the primary technology drivers include applications in the cleanup of hazardous waste, unexploded ordnance, autonomous navigation in unknown terrain, and in space teleoperation. This work is performed largely for government owners, including the U.S. Armed Forces, National Aeronautical and Space Administration (NASA), Environmental Protection Agency (EPA) and the Department of Energy (DoE). Some of the advances in these applications will be introduced below. The construction industry in general remains skeptical about the ability of most of the existing robotic technologies and the corresponding robot prototypes to perform useful tasks on construction sites with acceptable levels of reliability, quality and productivity.

Purdue University's Failure Tolerant Operation of Robots

Purdue University, with support from Sandia National Laboratories, completed the development of a control system for failure tolerant kinematically redundant robots. A failure tolerant robot is one which is minimally affected by the failure of any of its joints. Such robots are ideal for moving fragile or expensive payloads, conducting time critical tasks, and working in environments which make repairs to the robot prohibitively expensive. Examples include critical construction tasks, operations in space, the deep sea and areas contaminated by radiation and/or chemicals.

A practical method of achieving failure tolerance in a robot design is to provide more actuated joints than are necessary for the intended task. These "redundant" degrees of freedom can thus be used to replace tool motions lost by the failure of a joint. While simply duplicating the joints of a robot is one way of achieving a redundant design, it is not the most economical. The inverse kinematic routines of this class of redundant robot can further enhance its fault tolerance capability.

Jet Propulsion Laboratory's Lightweight Survivable Rover

One of the JPL (Pasadena, California) projects of potential interest to construction robot developers and users is the Lightweight Survivable Rover (LSR). This research develops, demonstrates and quantifies new rover technologies that will enable low mass, volume and power unstructured surface exploration over diverse terrain and latitudes, thereby increasing capabilities for *in situ* soil sample collection. The target technology applications include mobile sample acquisition, packaging and return functions of the NASA Mars Surveyor Program (MSP), and possible missions beyond. Recent work demonstrated important technology proofs of concept for areas including lightweight/collapsible mobility implementation, improved thermal controls, and computation efficient hazard avoidance. Derived concepts are now being applied to design of a flight science rover for the MSP'01 mission.

In 1997, LSR work focused to a new rover prototype for Mars Sample Return (MSP '05). The function of this rover is to quickly retrieve, in as little as one diurnal cycle, previously cached material in near proximity to a companion ascent vehicle. JPL demonstrated and benchmarked such system developments in earth-simulated science operations, also performing component-level tests in difficult environmental conditions. Work of the LSR task began in 1996; system level results to date are illustrated by the LSR-1 integrated technology prototype.

Carnegie Mellon University's Natural Landmark Navigation and 3-D Workspace Modeling

The CMU Natural Landmark Navigation program's objective includes the development and demonstration of visual perception technology for robotic navigation through an unstructured site. This technology will enable robotic vehicles to traverse such a site, visiting rocks or other objects designated as targets, without use of lander cameras or range sensors. The approach locates and tracks features from the rover's on-board cameras, and determines the rover position through triangulation and filtering against dead-reckoned estimates of vehicle motion. Relative navigation about a site is achieved by tracking distinct image features, such as prominent rocks or ledges, and computing vehicle position in a local coordinate frame.

The components of the system include landmark selection, based on color and texture; landmark tracking, using local operators; and relative position estimation. Recently completed goals include development and demonstration of visual tracking and position estimation. The goal for tracking is to predict and verify the coordinates of up to five targets. The goal for position estimation is to demonstrate a relative position accuracy of 30 cm.

Among the recently developed planning tools, *Artisan* is a software package that, with minimal human interaction, builds a 3-D model of the robot's workspace. It provides a much richer understanding of complex, interior work environments than what can be gleaned from conventional 2-D camera images and the operator can view the work space - in a virtual context - from arbitrary viewpoints without repositioning the cameras. This graphical "virtual world" helps operators control remote equipment and is essential to telerobotic planning and motion control thus allowing remote operators to focus on work rather than on the robot. Therefore, *Artisan* serves as a tool for current remote robotic applications and represents a bridge to fully automatic remote operations.

National Robotic Engineering Consortium

This national venture located in Pittsburgh, Pennsylvania, is active in a number of advanced robot application areas, including space, agriculture, construction equipment, and hazardous site remediation. Several projects relevant to construction industry robotics are summarized below:

Chernobyl Nuclear Reactor Containment Structure Stabilization: As a result of the April 1986 catastrophic nuclear accident in the Chernobyl Unit 4 nuclear reactor, shortly after the accident an external containment structure, or Shelter (known in the West as "sarcophagus") was erected. Much of the Shelters structural support is provided by the remains of the original building, the structural integrity of which was severely compromised by the accident. The Shelter itself is showing signs of deterioration and its own integrity is dubious. For remediation of Unit 4 to proceed with minimal risk to the external environment, it is essential that the Shelter be structurally sound throughout all cleanup operations. This program is intended to develop and deploy a telerobotic structural diagnostic system consisting of a radiation hardened remote delivery platform and characterization tools capable of performing a significant structural evaluation and monitoring mission within the Chernobyl Unit-4 Shelter. Initial deployment will be in a relatively benign portion of the Shelter to demonstrate in-field capabilities. These proving missions will be followed by entries into areas that pose significant challenges in the form of rugged terrain, high radiation, and complete darkness. The robot, dubbed *Pioneer* will initially deploy devices to map radiation, temperature and humidity; acquire core samples of concrete structures for subsequent engineering analysis; and make photo-realistic three-dimensional maps of the building interior. The first year of the project is divided into several phases: the first phase, near completion, will establish the functions and requirements and a conceptual design basis for the subsystems and integrated robot system. Detailed design, fabrication and integration will occur in Phase II which will conclude with a documented factory acceptance test in Pittsburgh. In Phase III, all hardware will be shipped to the Shelter. Installation of the system in the Shelter, training of Ukrainian operators and cold testing will constitute the initial part of Phase IV, which ends after the first hot deployment. Cold tests and the initial hot deployment will be supported by technical representatives of the American development team. The Department of Energy's International Nuclear Safety Program initiated the development program and is responsible for definition of the application scenarios. DoE employees of Pacific Northwest National Laboratory and Lawrence Livermore National Laboratory are responsible for technical oversight. RedZone Robotics, Inc., of Pittsburgh is developing the Pioneer robot and its control unit. NREC will develop the core sampling unit; NASA's Jet Propulsion Laboratory will add force/torque sensing and control to that device, as well as data on the drill's response to coring various materials. NREC and NASA Ames (also in collaboration with the University of Iowa) will develop the photo-realistic 3D mapping capability. Westinghouse Corp. will develop radiation, temperature and humidity sensing capabilities. The deliverables to Shelter are the deployment robot and associated control console and power distribution unit; the photo-realistic 3D mapping system (hardware and software); and the remote core sample acquisition system. Technical support of cold testing in Unit 4 and of the initial hot deployment are also deliverables. The deliverables to the NREC Core Technologies Library are the 3D mapping and visualization package, and the intelligent core sampling system. The robotic delivery platform is to be fabricated by RedZone Robotics, Inc. of Pittsburgh, Pennsylvania.

Demeter Automated Harvesting System: Land clearing, as well as agriculture represents a significant opportunity for previously developed, NASA-funded robotics technology. Field operations are repetitive and structured which decreases complexity and cost, improving the viability for commercial terrestrial applications. The *Demeter* project is developing a next-generation self-propelled hay harvester for agricultural and related operations. *Demeter* has proven its ability to exceed typical manned productivity and quality, most recently, achieving the project's 100-acre autonomous harvest milestone. *New Holland* North America, Inc is the corporate sponsor, defining performance and reliability specifications for the *Demeter* system. In addition, *New Holland* provides the development machines, engineering support, and direct funding to develop commercial integrations of the *Demeter* technology. NASA Ames, VEVI-based Supervisory Console, and JPL, wireless communications for mobile robots, have also become partners of the *Demeter* project. Development and testing for the robotic harvester began at the NREC facility. The 2nd generation harvester was built and tested at New Holland's R&D center in New Holland, Pennsylvania. Field testing has been conducted in New Holland and Hickory, Pennsylvania, and Garden City, Kansas. *Demeter* is currently stationed in El Centro, CA for the next 6-9 months. All field operations are in true production fields owned by local farmers (*Demeter* must maintain production harvesting quality). The deliverables of the *Demeter* project are software. Software developed under the program will be licensed to *New Holland.*

RoboDozer: NREC, along with the Field Robotics Center at Carnegie Mellon, is working on remote *Caterpillar* D4 bulldozer (CAT 850C) for the purpose of interfacing it to the ROBOCON (Robotic Construction) system. The goal will be to use the platform as a heavy earthmoving system to train operators and to experiment with human factors parameters to optimize human performance. The ultimate goal is to compare the performance of a human operator sitting in the same machine, to that of a remotely-located operator with simple visual and numeric feedback, motion-platform chair, etc. These results will be useful to several agencies intending to perform remote excavation operations, and will aid in the training of future remote equipment operators.

Autonomous Loading System: The ALS project is developing technologies with the intent to improve the productivity and reduce the cost of mass excavation. In a typical mass excavation application, a loading machine digs material from a face and dumps the material in a truck, with a throughput of hundreds of trucks per day. The process is repetitive and continues day and night and in most weather conditions. The type of loading machine and truck can vary, as can the material to be loaded which may range from sand to hard rock. Other issues include maintaining safety of all machines and personnel in the loading area and coordination of multiple machines to achieve a prescribed goal.

In addition, NREC is working on Autonomous Materials Transportation system, of which the initial objectives were presented in the 13th ISARC Proceedings.

Stanford University's High-Performance Control of Flexible Manipulators

Stanford University activities in high-performance control of flexible manipulators pursue general theoretical advances in automatic control theory that can be applied to a variety of robotic systems. This research is primarily conducted on three hardware platforms: a Single-Link Flexible Manipulator with complex dynamic payloads, a Two-Link Flexible Manipulator with a mini-manipulator at the end effector, and a new hardware platform: a Two-Link Flexible Manipulator with two mini arms. There are three major thrusts of this research:

1. Adaptive Control of Manipulators with Complex Dynamic Payloads: This research addresses problems encountered when robots manipulate payloads that possess significant internal dynamics. The goal is to have the robot system perform precision position control of the payload while making sure the internal dynamic motion of the payload is well damped.
2. Object Manipulation with a Two-Link Flexible Manipulator with Two Mini Arms: This research addresses the issue of planning and object manipulation with a flexible manipulator. The new hardware platform consists of a two-link flexible-joint manipulator carrying two mini arms. This new platform allows research in the areas of planning, manipulation, assembly, and cooperation with other hardware systems.
3. End-Point Impedance Control for a Multiple Link Flexible Manipulator with a fast Mini-manipulator: This research is an extension of previous work involving macro-mini systems where the macro is a flexible, multi-link system. This work involves extending the control theory for this type of system to allow contact with the environment, regulation of the contact forces, and explicit control of the end-point impedance. This work responds to the concerns of robot system users at NASA that there is a need for manipulative control, especially force and/or impedance control, for mini systems mounted on large flexible space macro robots.

Wearable Computers

A number of new implementations of wearable computers produced in recent years viable and mature commercial applications ready to be transferred into the construction industry practice. As one example, ViA, Inc. of Minnesota features a full-function personal computer in a person-wearable form. The computer weighs less than 0.5 kg, along with a flexible belt packaging to support the computer. The memory includes a Cyrix Media Gxi and 5520 chip set (180 MHz) with 32 or 64 MB DRAM. Standard software environment includes Microsoft Windows 95 or Windows NT, and BIOS with advanced power management, ACPI compliant. Mass storage includes a standard 2.1 GB 2.5 inch IBM disk drive, with various options available for the maximum storage of 3.2 GB. Input/output features include full duplex audio for speech recognition, SVGA video for CRTs and LCDs, two RS-232 serial communication ports, two serial universal bus ports, mouse and keyboard ports. Peripheral device options include 6.5 inch diagonal, 640x480 pixel TFT color flat panel display, audio headsets and head mounted displays. These computers are claimed to be dust, water and shock resistant.

A number of possible construction applications of wearable computers exist. With the use of wireless Internet connections, these computers provide a way for real time video, audio and data communication between the construction site and the corporate head office, with possible links to the design offices and subcontractors for automated design- construction integration and real time project control. Ongoing work in these areas takes place in several institutions, including Purdue University and the University of Illinois.

Conclusions

The amount of activity underway in the United States in the area of robotics is very large. There are signs of growing interest in robotics in the areas of industry which are users of construction services. For example, in November 1997 Gas Research Institute organized 1997 a Robotics Workshop for the natural gas utility industry. This workshop, conducted in Tarrytown, New York, was attended by R&D personnel from gas utility firms, as well as personnel from engineering firms providing technical solutions to the inspection, maintenance and repair of aging gas utility lines in eastern United States.

American Society of Civil Engineers (ASCE) organizes biennial conferences on Robotics for Hazardous Environments - the next such Conference is scheduled for late April 1998 in Albuquerque, New Mexico. Papers will be presented by researchers and developers from a number of U.S. government, academic and industrial research centers on topics such as design and control of flexible manipulators, current work on flexible and many-jointed robotic systems, motion planning for serpentine robots, remote sensing and modeling of unknown environments, autonomous configuration of sensors and actuators through innate learning, rendering inversion in the automated construction of virtual environments, all purpose remote transport systems, robotic workcells for hydraulic cement mortars, "smart" attachments for utility damage prevention, robotic underwater vehicles, robotic 30-ton bridge cranes, and technology transfer of space robotics.

A number of robotics related developments not mentioned in this paper are taking place throughout the country - some of these will be described by others in these proceedings. Much work remains to be done to bring about successful implementation of robotics on American construction sites. Full cooperation of all parties to the construction project is essential. This is still challenging in view of the fragmentation of the work activities and for many other reasons described in the previous ISARC proceedings. However, each new technical development, and the growing corporate recognition of the viability of automation for construction tasks, will likely make this goal attainable.

World Wide Web Resources:

National Robotic Engineering Consortium	http://cronos.rec.ri.cmu.edu/
Carnegie Mellon Robotics Institute	http://www.ri.cmu.edu/
NASA Space Telerobotics Program	http://ranier.oact.hq.nasa.gov/telerobotics_page/
Jet Propulsion Laboratory Robotics Section	http://robotics.jpl.nasa.gov/
ViA, Inc.	http://www.flexipc.com