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Automatic Planning and Programming for Robotic Construction of Planetary/Lunar Structures

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Automatic Planning and Programming for Robotic Construction of Planetary/Lunar Structures

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ABSTRACT

Many difficult material handling needs exist in remote unstructured environments. Currently these operations are accomplished using personnel in direct contact with the hazards. A safe and cost-effective alternative to this approach is the use of intelligent robotic systems for the excavation, handling, transport and manipulation of materials during remote construction operations. A robotic system designed for these tasks has been developed at Sandia National Laboratories which successfully integrates computer controlled manipulation and mobility to deliver these needed robotic capabilities in remote applications such as planetary operations. The mobile robot, RETRVIR, incorporates advanced developments in the integration of sensors, advanced computing environments, and graphical user interfaces. The addition of these elements in the control of remotely operated equipment have shown great promise for reducing the cost of remote construction while providing faster and safer operations.

* * Peter T. Boissiere was a member of the Intelligent Systems Department I while this technology was developed.

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INTRODUCTION

Hazardous operations which involve the dexterous manipulation of materials in remote space environments have, in the past, been completed by specially equipped astronauts. Use of humans in such hazardous operations is under increased scrutiny due to high costs and low productivity associated with providing protective clothing and environments. Remote systems are needed to accomplish many tasks in planetary operations, in which the exposure of personnel to radiation, chemical, and other hazardous constituents is unacceptable. Traditional, remote, manual field operations have, unfortunately, proven to have very low productivity when compared with unencumbered human operators. The reasons are coupled to the difficulties in standard remote operations. The systems are typically teleoperated, with live video as the sole operator feedback. Severely limited visibility, a lack of the sense of touch, and an operator's responsibility to not damage anything with the remote system, all result in degrading an operator's performance.

Sandia National Laboratories (SNL) researchers have developed the mobile robot RETRVIR to deliver highly dexterous, sensor controlled motion to remote sites. In particular, this most recent focus of the RETRVIR development activities has been the integration of advanced operator interfaces to complement RETRVIR's on-board system capabilities. [1] Computer models and real-time sensing allow automation and increased safety of many difficult operations, such as manipulator deployment, approach to, and grasping of objects. The high-force capability of RETRVIR allows controlled excavation using specialized tools.

There are many unique features in the RETRVIR system which directly improve remote operations. [2] The graphic models available to the operator when coupled with vehicle error detection and correction capabilities, greatly reduce operator stress and fatigue. The model-based motion planning capabilities increase the safety of the remote operations by allowing the operator to preview all movements before any activity takes place. Finally, pre-programmable, repeatable, robot systems improve productivity by reducing the time to execute remote repetitive tasks.

Figure 1. RETRVIR

SYSTEM DESCRIPTION

The complete mobile manipulation system consists of a remote manipulation and excavation robot (RETRVIR), incorporating a remotely piloted vehicle and hydraulic manipulator, and a mobile control center which houses the operator control station and a transportation/work area for the robot.

The RETRVIR testbed in its current configuration is shown in Figure 1 and consists of a Honda Pilot off-road vehicle modified for remote operations by installing actuators on the gear shift, throttle, brake, and steering mechanism. The on-board computing systems and communication modules were placed at the original location of the driver to provide a weight distribution similar to that of a standard unmodified Honda Pilot. The control computers use sensory information and models of the vehicle performance to map and modify the remote driver

commands into control inputs for the vehicle control actuators. Other equipment includes cameras for live video, a global positioning system, and various sensors to monitor on-board system status and others that monitor external parameters, such as nearby obstacles. Electrical power for the added equipment is produced by a generator mounted on the vehicle.

The seven-foot robotic arm, mounted on the front of the vehicle, is a TITAN IITM manipulator from Schilling Development Inc. This hydraulic manipulator has six degrees of freedom, and is capable of lifting up to 650 pounds. As shown in Figure 1, the Titan manipulator is mounted on the front end of the Honda to provide maximum forward reach. The vehicle's rear mounted engine counter balances both the arm's weight (180 lb.) and any anticipated payloads. Hydraulic power for the manipulator is produced by an on-board hydraulic power unit.

Figure 2. RETRVIR Control Center

The Mobile Control Center (MCC) is built into a 24 foot dual axle trailer to allow the RETRVIR testbed to be tested in varying environments. The operator control console and other hardware and controls are mounted in the front end of the trailer. The control center is built around an SGI (Silicon Graphics, Inc.) UNIX-based graphical workstation, with a large central monitor. Smaller video monitors are included for real-time visual feedback. Other equipment includes video and digital communication systems, a VME rack used for image processing, and a global positioning system. The RETRVIR robot is transported in the back of the trailer which is also equipped as a workshop for minor repairs and maintenance of the vehicle. The trailer is equipped with a generator, air conditioner, heaters, lights, and electrical power conditioners to enable self-contained operation.

During operation, the operator sits in front of a large computer console (shown in Figure 2). Primary interactions occur through a mouse, using a point & click interface for the majority of the commands. A second input device, a 6 degree of freedom space ball, is also used during shared control of the vehicle and the manipulator. Also, the keyboard is used to specify objects within the graphic interface.

Communications between the vehicle and MCC occur by means of two commercial Radio Frequency links. Digital and video feedback are transmitted on separate frequencies. The communications system allows operation of RETRVIR as far as five miles away from the control center trailer.

Using an enhanced version of the Sandia developed KRITIC supervisory control structure [3], RETRVIR's on-board computers use sensory

information and models of vehicle performance to map and modify the remote driver commands into control inputs for the vehicle actuators. The KRITIC architecture consists of a modular parallel structure where each module is responsible for a different part of the overall system behavior. The basic function of the KRITIC controller is to monitor motion commands, evaluate the impact of those commands with respect to the robot's operating environment, and modify the commands if necessary to achieve robot motion in a safe manner. The basic assumption is that the motion command comes from a supervisory level. However, the command generator—whether it is human or a computer path planner—may not know all the constraints that can prevent the completion of a commanded operation. Consequently, the motion commands are assumed to

be valid, but they may require adjustments to account for environmental and robot constraints.

The computing structure of RETRVIR is shown in Figure 3. As indicated, a UNIX-based supervisory system communicates with a VME-based on-board multiprocessor environment and a VME-based real-time base station. VxWorks™ provides the operating system needed for coordination of multiple CPUs, of which there are four on the vehicle. One CPU is responsible for the command and control of all functions relating to the vehicle. Two CPUs are in control of the robot manipulator; one controls the arm trajectory while the other acts as the joint servo controller. A fourth CPU is used to control a global positioning system and navigation system. A global memory management system allows all CPUs to share data.

Figure 3. RETRVIR Computer Architecture

OPERATOR INTERFACE

The principal goal of research into the operator interface for RETRVIR was to make programming and operation of the vehicle easier in unstructured environments for untrained operators. To accomplish this end, the operator needs to be able to act in a supervisory role: that is, to send task level commands instead of low level control commands whenever possible. However, when shared control is required, the operator can provide direct input into the on-board vehicle control systems. This input will be overridden if commands are sent that are hazardous to the system, such as running the manipulator into the vehicle, or driving the vehicle into a sensed obstacle.

In order for the robot to interact automatically with its environment, the environment must be known. The operation of a robot in an unstructured environment necessitates the need for knowledge about the environment, which, in turn, forms the philosophy [4] for the operator's interface to the system:

- If you have knowledge, use it
- If you don't have knowledge, obtain it
- If you use knowledge, assume it is incomplete.

Knowledge about the robot, such as its geometry, kinematics, etc., or, possibly, even the surface terrain of the work environment obtained from satellite based topological maps, becomes the basis of the world model used by the robot. Additional information is added to the world model through sensors, such as the Visual Targeting System (described later), which allows the robot to learn about its environment and further protect itself. However, the knowledge that is in use must be assumed to be incomplete, both because of the limitations of the sensors and because of the changes in the real world due to RETRVIR's interactions. Real time sensors, such as the obstacle avoidance system tied in to KRITIC, add safety where the model is incomplete.

Integration of sensors with model-based control concepts allows rapid programming of safe operations even for inexperienced personnel. Computer controlled autonomous operation greatly reduces the time for remote operations while improving safety.

Examples are discussed in the ADVANCED FUNCTIONS section below.

As shown in Figure 4, the interface incorporates real-time computer models to view the entire operation of RETRVIR, as well as graphical images that display status information and all available system commands. The graphical display console is divided into three sections: a world model, a graphical dashboard, and a command menu system.

WORLD MODEL

The world model is the control system's view of the environment. For this reason it is critical to provide as much information as possible about the robot itself and the workspace surrounding it. The model can then be used to anticipate imminent collisions and help insure safe operation for autonomous operations.

The world model is also important in assisting the operator in task planning. This information is presented to the operator in a 3-D graphics window. The world model allows the operator to see the position and orientation of the vehicle, manipulator arm, and other modeled parts of the environment at all times and from any point of view. This greatly enhances the operator's perspective of the system beyond the live video signal. The operator can also interact with the world model to preview all motions before execution to insure safe operation. The world model is also used to define other vehicle and manipulator functions such as selecting a goal position for the vehicle in preparation for autonomous driving, or defining the size and location of a site for autonomous excavation.

The world model is an application of the Graphical Programming paradigm [5] as it has been developed by Sandia for application to robot system control. This technology has integrated sophisticated 3-D graphical modeling into the real-time control of robot systems. Graphical Programming is distinguished from conventional off-line programming by real-time updating of the graphical model to allow continual validation of robot motions. The RETRVIR system uses a SGI (Silicon Graphics, Inc.) graphics engine to allow real-time update rates of the world model. IGRIP [6] is currently being used as the modeling software. This window appears in the center of the graphical display. See Figure 4.

The operator controls the major functions for vehicle control, such as engine-on or gear selection, from the driving menu. A switch for teleoperation of the vehicle allows the operator to drive the vehicle in a shared control mode. A space ball is used for teleoperation allowing simultaneous control for steering, throttle, and brake. KRITIC control parameters are selected from this menu. A camera select button controls a video switcher on the vehicle. There are six cameras mounted on RETRVIR. A pan and tilt mounted camera on the top of the vehicle is well suited to the driving of the vehicle. Other cameras are used for precise vehicle and manipulator positioning and as part of the Visual Targeting System (see below).

The manipulator menu allows the operator to control the robotic arm in either a programmed or shared control mode. Commonly needed vehicle functions for engine, hydraulics, and cameras are repeated, so that the menu is self contained. Basic *automated* manipulator tasks, such as stowing and unstowing the arm, and tool exchange are direct examples of supervisory level control. Gripping tools that are mounted on the side of the vehicle require very precise movements to insure proper alignment and to avoid damaging the vehicle. Using knowledge of its environment, the robot is programmed to perform these demanding tasks automatically. The operator need only send a task command and monitor the system's performance.

The prime function of the manipulator arm is to grasp and manipulate objects. Some objects, such as the manipulator's tools, have a known configuration and location and are incorporated into the world model *a priori*. When using a robot in an unstructured planetary environment, it is important to continually increase information available to the system, thereby allowing increased autonomy and increased ease of use. Dynamically defining objects important to the task the robot is performing is one way to increase the knowledge in the world model.

VISUAL TARGETING

The Visual Targeting System [7] is a computer vision system developed to locate objects, or targets, in space. It is based on stereo imaging. Any two cameras aboard the vehicle are used to present two video views of a scene to the operator. The location of corresponding features is identified in each image. The position and orientation of the cameras, the geometry of the calibrated camera models, and the corresponding image locations are all used to determine the 3-D location of the feature in space. Multiple target points can be combined to define the extent and

orientation of an object, or the position and orientation of a grasp point.

Typically, the vehicle will be driven to a location and the video cameras will be used to survey the area visually. When an object of interest is identified, the Visual Targeting System is used to locate the object. The operator types a name for the object into an object list, and this information then becomes part of the system's world model. Six buttons on the interface control the acquisition and control of targets by using the Visual Targeting System. Moving the manipulator arm to an object now becomes an automated function.

ADVANCED FUNCTIONS

Beyond the basic automated tasks of stowing, tool handling, and object grasping and manipulation, the system allows for the addition of much more demanding automated tasks. Autonomous digging has been used in the field demonstrations. Other functions include space platform construction and driving.

EXCAVATION - In preparation for autonomous excavation the operator must first tell the robotic system where to excavate. This is accomplished in one of three ways. First, the operator can use a mouse to define the extent of the desired hole directly from the graphical world model. Second, he/she can use the Visual Targeting System to directly select features from the work site. Third, the manipulator can be used directly to "touch off" on the ground at four points to define the extent of the excavation. Once the excavation has been setup, which takes minimal time, the excavator motions are previewed from the world model "off line" before any real motions take place. This allows the computing system to verify that the shovel path is within safe operating parameters. The operator may modify the motions if desired. After the setup is complete and the system is commanded to begin, the shovel is deployed, and digging proceeds. The operator is in a supervisory capacity during the operations and has the ability to modify, or stop completely, the excavation at any time.

CONSTRUCTION - The space platform construction was designed to test the ability of a remote manipulator robot in construction tasks similar to those needed for construction of a communication disk system and instrument platform. In this case, the construction consists of four towers, four connecting cross members, and two panels. The platform rack can be seen in the world model in Figure 4. The vehicle is driven to the site where the unassembled members are

located on a rack. The Visual Targeting System is used to locate the position and orientation of the rack in relation to the robotic system. The rack then becomes part of the world model. The operator interacts with the world model to determine the location for construction. Once the motions are previewed by the world model to verify reachability and safe operation, construction can proceed automatically. Again, the operator can interrupt at any time, or may be prompted to intervene if problems are detected. Field tests demonstrated successful automated construction of such platforms.

DRIVING - The automated driving function enables the operator to select a destination and a suggested path, and then take a supervisory role of monitoring while the vehicle drives autonomously. The world model is continuously updated using position and orientation data from the vehicle through the global positioning system and dead reckoning. Live video is also displayed at the control center. Additional help is provided through the ultrasonic obstacle avoidance system on the vehicle and the KRITIC control system.

CURRENT FIELD WORK

The RETRVIR experimental system has been deployed in terrestrial tests on several occasions during 1994. On May 2, 1994, RETRVIR carried out retrieval operations for the first time. The hazards associated with retrieving buried chemical and explosive materials in a landfill made excavation and retrieval a high priority, yet prevented technicians from entering and removing the materials. Combined automated and remote manual operations allowed RETRVIR to quickly and safely excavate covering soil, automatically approach unknown objects, and then grasp and remove objects from the uneven terrain of the site. The remote camera systems and high dexterity computer controlled robot arm allowed retrieved objects to be visually inspected and carefully placed in plastic bags. The retrieved objects were then driven to the entrance of the site for removal for laboratory analysis. Retrieval operations were continued for 2 days, and site technologists expressed delight in the ability of the system to respond quickly to a critical need to perform operations not possible using conventional approaches.

On September 26, 1994, the RETRVIR system was deployed to Jefferson Proving Grounds in Madison, In. for one week, to participate in field tests supported by the Navy Explosive Ordnance Disposal Technical Center. The purpose of these tests was to determine the current capabilities in

the areas of sensing and mechanical clearance of buried munitions. This test proved to be very valuable for the RETRVIR team: it allowed the system to be tested under real world conditions, and for the system's strengths and weakness to be evaluated.

From February 27 to March 14, 1995, RETRVIR carried out retrieval operations in a remote bomb disposal pit used to store submunitions (bomblets) at the Department of Energy's Tonopah Test Range. The pit, which was approximately twenty feet long and ten feet wide, contained over two thousand bomblets as well as many remnants from other large ordnance such as tail cones and fins. RETRVIR's versatility allowed the robot to enter the pit and retrieve over eleven hundred individual bomblets as well as excavate and remove many pieces of scrap metal. Control of RETRVIR was accomplished from the system's control center stationed three thousand feet away from the waste pit. Once the bomblets were removed they were deposited at a processing pad where shaped charges were attached to the munitions to render them safe.

These actual field tests in remote sites indicate that RETRVIR unique control technologies should perform properly in remote planetary environments as well.

FUTURE RESEARCH

Perhaps the most compelling area of future work entails rapid building of the world model. Most of the advanced functions will necessarily require additional information about the environment. For example, the ability to add topological maps to the model will aid automated navigation work. Other ideas include using 3-D sensors to add surface information. Object recognition and registration need to be developed more fully. In addition, images will be added as texture maps to modeled parts to enhance realism. Video overlays will allow the operator to work more directly from the world model. An increased ability to interact with objects directly in the world model instead of an object list will provide a more intuitive operator interface.

SUMMARY

The use of knowledge in the control of a remote robotic vehicle designed for dexterous mobile manipulation has eased the burden placed on the operator and allowed for the automation of both simple and complex tasks. A graphical programming environment, sensor based control, and the ability to add structure to the environment by interactive model building have allowed even advanced tasks, such as automated excavation and instrument platform construction, to be performed autonomously. This high level of autonomy has not sacrificed the ability of the robot to be used in a shared control mode during teleoperation. The change of control from teleoperation to automation can be performed seamlessly by the operator. Actual field use of RETRVIR in the examination and excavation of compressed gas bottles in the Sandia National Laboratories Bottle Pit and the excavation of bomblets from the Tonopah Test Range in Nevada have given the developers the opportunity to successfully use RETRVIR in real world environments. Further automation of tasks in hazardous unstructured environments is possible and will rely heavily on the ability of the robot to fully assess its environment through dynamic world modeling and other sensing systems.

COMMERCIALIZATION

The RETRVIR technology is becoming commercially available through BEAR, Inc., with the help of Sandia National Laboratories' efforts to transfer technology to US industry.

ACKNOWLEDGMENTS

Several members of Sandia's Intelligent Systems and Robotics Center have contributed to the success of RETRVIR both directly and indirectly. Some specific developers who contributed time and effort to the success of the program include:

- Chris Wilson, who contributed to the mechanical design and, more recently, to the Visual Targeting System;
- Brian Rigdon, Bill Davidson, and Scott Irwin, who contributed to the communications software used in this project;
- Brian Jones, who contributed to the models used in the graphical user's interface;
- Mike Martinez and Mike Kuehl, who spent many hours putting the system together.

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