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APPLYING ROBOTICS TO HAZMAT

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ABSTRACT

The use of robotics in situations involving hazardous materials can significantly reduce the risk of human injuries. The Emergency Response Robotics Project, which began in October 1990 at the Jet Propulsion Laboratory, is developing a teleoperated mobile robot allowing HAZMAT (hazardous materials) teams to remotely respond to incidents involving hazardous materials. The current robot, called HAZBOT III, can assist in locating, characterizing, identifying, and mitigating hazardous material incidences without risking entry team personnel. The active involvement of the JPL Fire Department HAZMAT team has been vital in developing a robotic system which enables them to perform remote reconnaissance of a HAZMAT incident site. This paper provides a brief review of the history of the project, discusses the current system in detail, and presents other areas in which robotics can be applied removing people from hazardous environments/operations.

INTRODUCTION

Responding to incidents involving hazardous materials can be extremely dangerous and requires specially trained HAZMAT personnel. Upon arrival to an incident site, the HAZMAT team must first try to determine what types of materials are involved and what threat they present. Unfortunately, records may not be complete or easily accessible and the only way to determine the type and extent of the spill is to send in HAZMAT team personnel.

First entry into incident sites where the types of materials involved have not been identified is particularly dangerous. Members of the team must take all precautions and wear full protective gear including a self contained breathing apparatus and a multi-layer protective suit as shown in Figure 1. This type of protective gear significantly restricts mobility, allows only 15 to 30 minutes of work time, and is extremely hot and stressful on the wearer. Moreover it can take up to an hour for the entry team to suit up once it has arrived at the incident site, delaying identification of the hazard.

The Emergency Response Robotics Project at JPL is prototyping a mobile robot system that can be quickly deployed by HAZMAT teams enabling remote reconnaissance of an incident site without risk to team personnel. The primary goals of the project are:

Figure 1: HAZMAT Team Personnel in Protective Suits

- Develop a teleoperated mobile robot system which can be easily operated by HAZMAT team personnel allowing remote access to an incident site (which may require climbing stairs, unlocking/opening doors, and operating in confined spaces), identification of chemical spills via visual inspection and remote chemical sensing, as well as aid in incident mitigation/containment.

- Work directly with the end-user of such a system (JPL Fire Department HAZMAT team) to establish system requirements as well as use and critique the system under development.

- Work to transfer technology and concepts developed under the project to industry.

These initial goals of the project are discussed in detail in [1]. Other examples of the application of robotics to hazardous material operations are given in [2,3,4].

Several commercially available robotic vehicles were evaluated and two REMOTEC[1] ANDROS Mark V-A systems were procured. (A reference book which covers many of the commercially available and research robots for

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[1]REMOTEC, 114 Union Valley Road, Oak Ridge, TN 37830

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hazardous operations is [5].) The ANDROS robot has a variety of important features needed for the project including its rugged construction, track drive system (enabling stair climbing), manipulator, on-board battery power, and sufficient size to support addition of equipment. Communication between the robot and operator control station is achieved by a 100m tether.

The next section of the paper briefly describes the initial modifications to the ANDROS robot undertaken in the first year of the project leading to the HAZBOT II system. (The name HAZBOT I being given to the "as purchased" system.) The section following this discusses the development of HAZBOT III, a major rebuild of the ANDROS robot. The current status of the project and future plans are then presented. Finally, other areas of potential use of HAZBOT or similar robotic systems are discussed.

HAZBOT II

The most important factor in the development of the HAZBOT II system was training and experimentation with the JPL Fire Department HAZMAT team to determine their requirements. This testing revealed the need for several modifications. One of the most important was the redesign of the operator control panel. The control panel supplied with the system, shown in the bottom of Figure 2, used an array of simple toggle switches to actuate a joint in the robot manipulator. For example, one switch was labeled elbow up/down. This type of control was very difficult for the trainees to master because whether or not the elbow joint caused the forearm of the manipulator to actually move up or down was dependent on the current position or configuration of the manipulator. This type of control therefore led to many mistakes during operation of the manipulator.
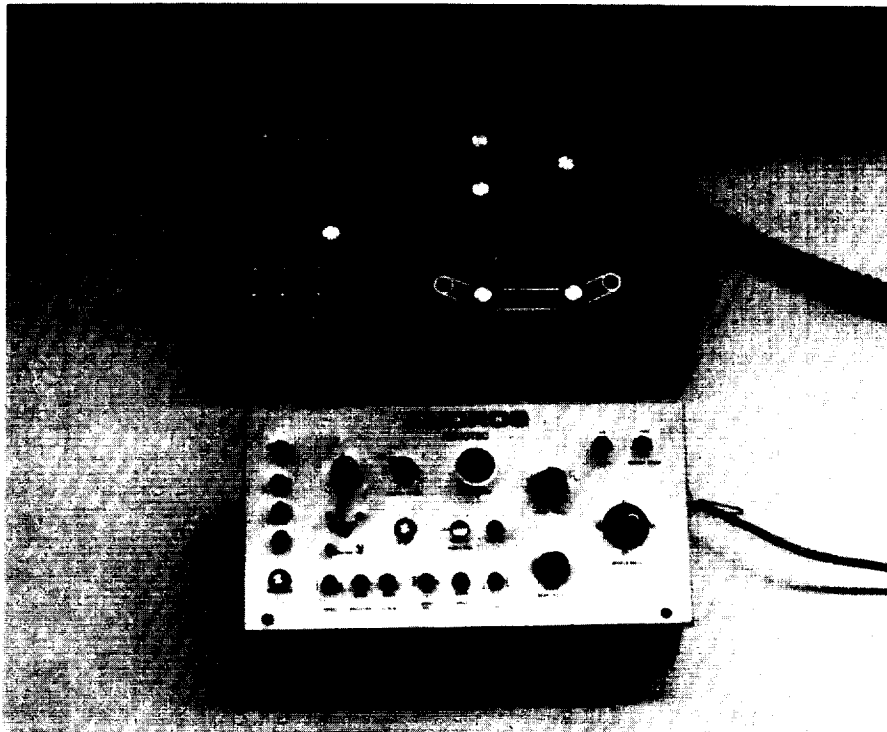

Figure 2: REMOTEC Control Panel and JPL Redesign

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A new control panel was constructed that used a simple side view graphic of the robot with controls for each joint placed at the corresponding point of the drawing as shown in the top of Figure 2. The toggle switches were replaced with spring loaded potentiometers; for instance, rotation of the elbow potentiometer clockwise caused the elbow joint to also rotate clockwise. This system was found much more intuitive for the HAZMAT team personnel and led to far fewer mistakes during manipulation tasks.

The HAZBOT II system included a variety of other experimental modifications to the original REMOTEC vehicle such as:

* Development of specialized key tools for unlocking doors.

* Placement of the pan/tilt camera on movable boom allowing better viewing angles during manipulation tasks.

* Addition of a commercial combustible gas sensor often used by HAZMAT teams.

* Addition of a laser depth cuing system.

These modifications are described in greater detail in [6].

We have had active communication with REMOTEC, keeping them up to date on modifications to the system. The control panel redesign has been successfully transferred back to REMOTEC and is being used as a prototype for their new control panels. Currently we are identifying technology in HAZBOT III which can be utilized by REMOTEC in upgrading their own system.

Figure 3: HAZBOT II Unlocking Chemical Storeroom Door

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At the end of the first year of the project, a simulated HAZMAT reconnaissance mission was carried out by the JPL HAZMAT team using the HAZBOT II system. The mission (described in [6]) included: opening of the exterior door of a building which had a thumb latch style handle and deployment of a door stop; sensing around a chemical storeroom door for combustible vapors; unlocking and opening of the storeroom door (as shown in Figure 3); and operation in the very small storeroom locating a simulated chemical spill. The operator control station used for the mission, including video displays, the tether spool, and control panel, is shown in Figure 4.

Figure 4: Operator Control Station

Although the use of mobile robots in HAZMAT operations was shown feasible by this first year demonstration, a variety of issues were identified that must be addressed for the system to be used in real response missions:

- Redesign of the robot so that it can operate in environments that may contain combustible gases. This is particularly important in first entry situations where the type of hazard is unknown and potentially combustible.

- Redesign of the robot with a smooth profile and appropriate sealing so that is can be easily decontaminated after a mission.

- Improvement of manipulator in terms of speed and dexterity.

- Continued enhancement of the operator controls.

- Addition of tetherless operation to allow deployment of vehicle greater than 100m from incident site and increase its mobility.

The next section describes how these requirements and the lessons learned in the first year of the project have been used to develop the HAZBOT III system.

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HAZBOT III

The focus of the second year of the project was to significantly redesign HAZBOT I (the ANDROS robot that had not been modified in the first year) to meet the system requirements enumerated in the previous section. The primary motivation in design of the new system was the need for operation in Class I, Division 1 environments as defined by the NEC (National Electric Code): environments which contain ignitable concentrations of flammable gases. A two tiered approach was used to address this design requirement. First, all electrical components that may cause electrical arcs or sparks during normal operation were replaced with solid state devices. This included using solid state relays instead of mechanical relays and replacing the brushed DC motors with brushless motors. As a second precaution, all areas of the robot that contain electrical components that could fail and cause sparks are pressurized. The system was not designed to be hermetically sealed but rather to support a small pressure above atmospheric so as not to allow any combustible vapors to enter the system while in operation.

HAZBOT III incorporates the following modifications and features:

- A five foot reach manipulator with a 40 lb payload capacity.
- Parallel jaw gripper with 30 lb grip force.
- Smooth profile to ease decontamination and reduce possibility of snagging during manipulation tasks.
- Internal channels to support pressurization of manipulator.
- Provisions for two movable booms on torso (one currently being used for pan/tilt camera) which also include channels for pressurization.
- A Ross-Hime Designs[3] 3 DOF OMNI-Wrist.
- An AIM 3300[4] specific gas and general combustible gas sensor integrated into forearm and drawing samples in through tip of gripper.
- Use of all brushless DC motors.
- A wrist mounted camera to aid in manipulation tasks.
- Increases of up to 7.5 times in joint speed over original manipulator.
- Low backlash through the use of harmonic drives.
- Reduction of manipulator weight from 150 lbs to 100 lbs.

Other important features of HAZBOT III include a winch system which can be deployed by the manipulator, a microphone and speaker allowing 2-way audio communication, a front mounted tool holder, and an on-board pressure tank.

The chassis of the robot was also enlarged to house a VME type computer system and control electronics. The original ANDROS vehicle used a simple computer system with open loop control of the manipulator. The new VME system includes a 68030 CPU, closed loop control of the new 6 axis manipulator, a variety of analog and digital I/O, as well as room for expansion. Software has been developed using the VxWork[5] real-time operating system. This computer system provides a solid foundation for future development in coordinated manipulator motion, automation of sub-tasks such as tool retrieval/storage, as well as remote sensing.

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[3]Ross-Hime Designs, Minneapolis, MN 55414
[4]AIM USA, Houston, TX 77272
[5]Wind River Systems, Alameda, CA 94501

In early 1993, HAZBOT III was used to perform a second simulated HAZMAT mission in conjunction with the JPL HAZMAT team. The mission, carried out in the waste material storage facility at JPL, was modeled after an actual incident which had occurred at the site a year earlier. The mission included:

• Unlocking and opening an exterior gate to the facility.

• Locating a simulated spill through an inspection window in storeroom door.

• Unlocking and opening the door to the storeroom as shown in Figure 5 (utilizing the same keytool used to unlock gate).

• Deployment of absorbent pads on spill.

• Opening of cabinet from where the leak was detected.

• Visual inspection and identification of a broken container responsible for spill.
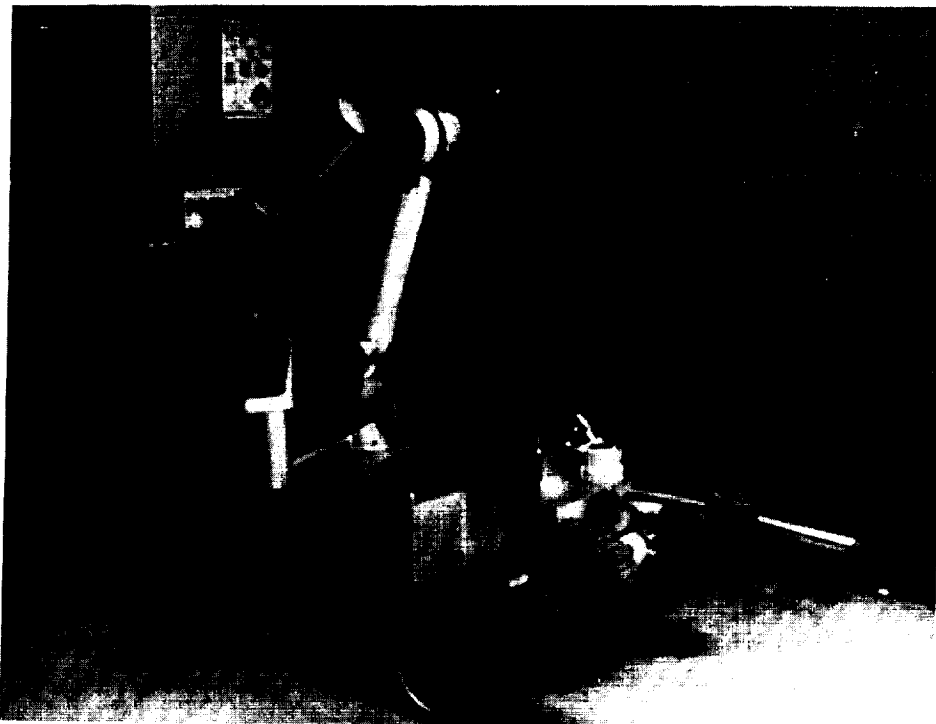

Figure 5: HAZBOT III Unlocking Storeroom Door

Most currently, the track drive sub-system is being upgraded with brushless motors and the pressurization system tested to complete the system rebuild for operation in combustible environments. Training and experimentation of HAZBOT III by the HAZMAT team will continue and help identify areas for continued development. Another simulated response mission is planned for late 1993.

FUTURE PLANS

The HAZBOT III system has addressed many of the requirements as defined by the Fire Department and project team. Two important issues which will be explored over the next year of the project are:

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- Tetherless operation - Depending on the type of incident, the robot may have to be deployed at a distance to the incident site greater than its 100m tether length. Also, complex site entry with multiple doors, stairs, etc. increases the chance of snagging the tether and delaying or ending the mission. The tether can be replaced by an RF link for two video signals, 2-way audio, and 2-way data communication.

- Operator controls - The control panel developed in the first year of the project for HAZBOT II has also been used for HAZBOT III. Although a significant improvement from the original design, a wide variety of enhancements can be made to make the operators job easier. (Operator fatigue is a major problem in teleoperations.) These include control algorithm development for coordinated manipulator motion, automation of simple sub-tasks such as tool retrieval/storage, addition of a graphical display indicating system status, sensor data, and vehicle kinematics. (One of the most redundant tasks undertaken by the operator is verification of manipulator position/orientation by scanning with pan/tilt camera.) Additional sensors will also be added to provide information to the operator. It is important to note that the users of this system are not researchers or engineers but Fire Fighters. The controls and feedback to the operator must be in a form that makes sense to them and allows them to confidently use the system for HAZMAT operations.

OTHER APPLICATIONS

Injury or loss of human life can be prevented by using robots in hazardous environments and operations. Robots are now routinely used in industry performing potential dangerous operations such as welding, painting, and material movement. More general purpose robots that can fulfill the need of HAZMAT and other dangerous operations are just crossing the line of economic feasibility. A few years ago, the use of robots by bomb disposal teams was unheard of, while today nearly every major municipal police department has a mobile robot at their disposal. (Newspaper articles describing the exploits of such systems are becoming ever more frequent.) These robots do not replace the highly trained and skilled people in police and fire departments, but rather provides an additional tool that can protect them from injury or death. Other areas for applications of mobile robots similar to the ones discussed here are:

- Mining operations - Not only in general mining operations but perhaps more importantly in gaining access to a mine after an accident. Often the build up of methane or other combustible gases keep rescue teams from entering a mine until it has vented; a system designed for operations in such atmospheres could explore the accident site immediately and help save lives.

- Remote Sampling - Unfortunately today we are faced with many hazardous material dumps which must be monitored on a regular basis. Mobile robots can be stationed at these sites to provide remote sensing and data gathering capabilities rather than repeatedly sending people into the area. Entry into newly discovered sites (for example, those found during military base closures) is very dangerous because the types of materials and the extent of the danger is unknown. Teleoperated robots enable people to remotely and therefore safely explore and classify these sites.

- Law enforcement - As mentioned above, mobile robots are now widely used for bomb disposal. Such systems have also seen duty in hostage situations and armed stand-offs. Robots provide law enforcement agencies remote eyes and ears helping to catch criminals with reduced risk to department personnel.

SUMMARY AND CONCLUSION

This paper has described the Emergency Response Robotics Project and the development of the HAZBOT robots at JPL. The project, currently in its forth year, is prototyping a teleoperated mobile robot for use by the JPL Fire Department HAZMAT team in responding to incidents involving hazardous materials. Key features of the current system include:

- Mobile operator control station with two video displays, custom control panel, and tether reel.

- Tracked mobility system with articulated front and rear sections allowing stairs to be traversed.

- Real-time computer system proving basis for future system development.

- Custom 6 DOF manipulator with integrated chemical gas sensor.

- System designed for operation in combustible atmospheres by using non-arcing electrical components (brushless motors) and internal pressurization.

Two simulated response missions have shown that the basic system is capable of first entry/reconnaissance type missions. Continued system development and training with the HAZMAT team will lead to a robotic system that can be used to respond to actual incidents involving hazardous materials thereby reducing the chance of injury or death of HAZMAT team personnel.

A critical factor in the system development is the close interaction of the project researchers and engineers with the Fire Department HAZMAT team and other safety personnel. This type of directed project and interaction with the end-user or customer must take place if robotics are to move from the laboratory to real-world application. Moreover, industry must be brought into the loop if this technology is going to be made commercially available in a timely fashion.

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ADVANCED TELEOPERATION
Technology Innovations and Applications

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ABSTRACT

The capability to remotely, robotically perform space assembly, inspection, servicing, and science functions would rapidly expand our presence in space, and the cost efficiency of being there. There is thus considerable interest in developing "telerobotic" technologies, which also have comparably important terrestrial applications to health care, underwater salvage, nuclear waste remediation and other. Such tasks, both space and terrestrial, require both a robot and operator interface that is highly flexible and adaptive, i.e., capable of efficiently working in changing and often casually structured environments. One systems approach to this requirement is to augment traditional teleoperation with computer assists -- *advanced teleoperation*. We have spent a number of years pursuing this approach, and highlight some key technology developments and their potential commercial impact. This paper is an illustrative summary rather than self-contained presentation; for completeness, we include representative technical references to our work which will allow the reader to follow up items of particular interest.

A BRIEF TECHNICAL OVERVIEW

Telerobotics technology development [1] is motivated by a desire to remotely perform complex physical tasks under human supervisory control. To date, robotic systems that have embodied significant supervisory (autonomous) control of their manipulation functions have been limited to highly structured tasks that were performed under favorable and certain conditions -- by definition not complex tasks, and not adaptive performance. This has fostered the widespread use of teleoperation, which at the other extreme from automation, is a characteristically laborious manual control procedure, historically applied to hazardous environments such as nuclear materials handling, underseas recovery, and recently, space shuttle operations. *Virtual environments* and virtual reality (VR) engineering are related and currently popular areas of technology development, wherein the human operator directly manipulates or experiences a modeled, rather than physical reality via computer-synthesis and appropiate input/output devices (e.g., master control gloves/stereo-immersive displays). There exists an important technical intersection of VR technology with telerobotics, most specifically with teleoperation: Virtual environments are useful tools for simulation and design, including task analysis, training, and on-line task preview and prediction. Thus, if VR can be efficiently integrated and physically calibrated with teleoperation systems, it has promise to assist the operator's on-line perception, planning, and control functions.

With regard to space applications, teleoperation systems could have important near-term roles in remote platform servicing, telescience, and lunar exploration, as already illustrated in Shuttle STS-RMS operations. However, the physical and logistical demands of space telemanipulation, particularly in less structured environments, will be high. Tasks can be physically complex and time-consuming, and the operator's manual dexterity and hand-to-eye motion calibration must be good. Further, the work will often be conducted under degraded observational conditions and thus be tedious and fatiguing. Operational uncertainties include obstructed viewing and manipulation, as well as the very disorienting effects of possible time-delay between the operator inputs and robot actions (a major obstacle to achieving desirable ground versus on-orbit operations). In the face of these collective challenges (which have their metaphors in other applications areas such as minimally invasive medical robotics and deep sea teleoperations), we have been trying to "computer-enhance" the performance of traditional teleoperation, and have made progress in the technical areas of redundant telemanipulator control, viewing systems, real-time graphics-based task simulation and predictive control, integrated operator interface design, systems-scale ground laboratory experiments and accompanying human factors data collection & analysis. The laboratory photographs of the next page give a sense of our system implementation; we comment below on our specific enabling technical advances (with supporting citations). For the reader seeking a detailed engineering overview of this work through end-1991, see reference [2]

ADVANCED TELEOPERATION TECHNOLOGY
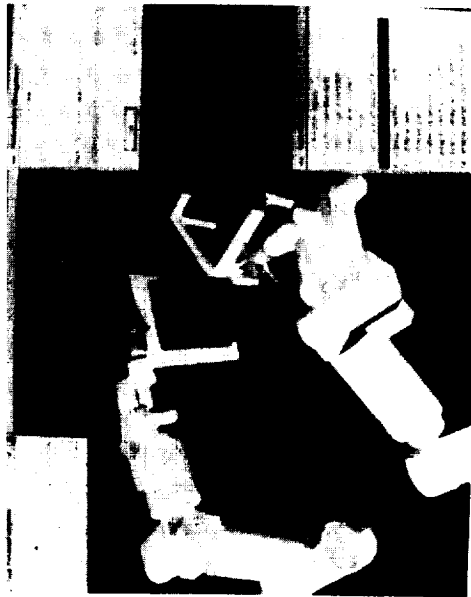## Validation Through Simulated Satellite Repair Task
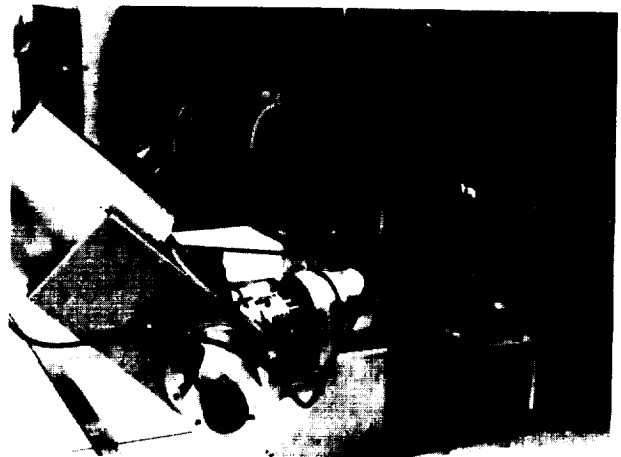
A main experimental thrust in our lab has been end-to-end system-level performance characterization -- formal experiment design, integrated system demonstrations, task instrumention & data capture, and human factors analysis. Collectively, the goal has been to quantify operator limitations, component technology requirements, and their interdependencies in the context of tasks simulated with realistically posed operational constraints (variable lighting, task geometry, time-delay, control & communication bandwidths, viewing & display limitations, etc.). Accompanying human factors issues are the assessment of technology impact on operator error, workload, and training, each in itself a significant risk and cost driver for space operations. As noted above, *advanced teleoperation* is computer-assisted telemanipulation, wherein the operator retains manual control of the task, but with extended functional capabilities and reduced cognitive complexity of task interaction. The computer assists we have developed to date encompass interactive task planning/simulation aids [3], graphics user interfaces for system programming/command/status display [5], and several modes of force-referenced teloperator control which are tolerant to operator positioning error (e.g., "shared compliance control" as described in [2,7] and references therein). In its most general form, advanced teleoperation entails sensory fusion and decentralized control, given that the system sensing, planning, and control functions are inherently distributed between operator and computer; to this end, we have developed some generalized control models and architectures for man-machine interaction at multiple levels of control abstraction, also related multisensor fusion models and techniques [6]. Regarding conventional controls, we have investigated a variety of kinesthetic position, rate, force-feedback, and shared compliance teleoperations modes [2,7]; these controls were first applied to dual six degree of freedom (d.o.f.) PUMA manipulators and more recently to high-dexterity eight d.o.f. redundant manipulators [8], whose controls development has included computer-based techniques of task redundancy management and visualization. We have quantitatively evaluated the operator utility of these these control modes, along with more traditional position and rate approaches, through simulated space servicing experiments [7]. As one example, we performed human factors-based experiments which telerobotically re-enacted high dexterity Solar Maximum Mission satellite repair procedures originally performed by astronaut extra-vehicular activity (EVA) during the 1984 space shuttle flight STS-13. Other supporting developments include real-time graphics environments which allow the operator to animate, analyze, and train on teleoperator tasks, and in a most general case, actually use the graphic virtual environment as a basis for reliable teleoperation under multiple second time delay [3,4]. We believe the area of *graphics-augmented reality* for teleoperation has particular promise in space applications and comment further by way of an illustrative example.

AN APPLICATION HIGHLIGHT

A significant obstacle to the acceptance of space telerobotic systems is the impact they might have on operational timelines of crew and platform resources. If a significant part of this burden could be shifted to ground operations, then the technology benefits of space robotics would be far greater. Serendipitously, utilizing ground operations would also free the operator control station of many space-borne implementation constraints, e.g., high degrees of computational power could be brought to bear. However, ground operation of a space robot performing a complex task confronts a basic system limitation in that robotic automation is not yet sufficiently generalized to allow conventional missions control by uplink sequencing of discrete high-level commands. Rather, the operator's continuous direct manual control and eye-to-hand perceptual coordination is required and unfortunately, the implied ground-to-orbit teleoperation approach will not alone suffice either. The problem lies in time-delay communications transit (2-10 seconds latency in current operations scenarios). The operator cannot "fly-by-wire" confidently or coordinate his eye-to-hand skills when causal action-reaction is on the order of seconds; indeed, people rapidly adopt a laborious move-and-wait behavioral pattern when round-loop control latencies are greater than .25 seconds.

Our approach to resolving this fundamental limitation has been to develop a class of 3-D graphics display which visually simulates the robot response in real-time immediacy to the operator's input. In essence, the operator interacts with a virtual task model. Thus, the critical details of the task (and robot itself) must be accurately modeled, and further, must be very accurately geometrically calibrated to the operator's time-delayed visual reality as displayed by down-linked video. In terms of practical implementation, this results in a 3-D high-fidelity graphics display which must be correctly registered and overlaid in translation, scale, and aspect re. a multi-camera robot workspace presentation. See the second page of laboratory photographs for a representative example. Our development of this *predictive graphics display* (with a calibrated virtual reality) has enabled us to preserve the operational features of teleoperation, and reliably operate with intermittent time delays up to 5-10 seconds. In a recent demonstration depicted in the lab photos, we, in coordination with colleagues at NASA Goddard Space Flight Center, performed a
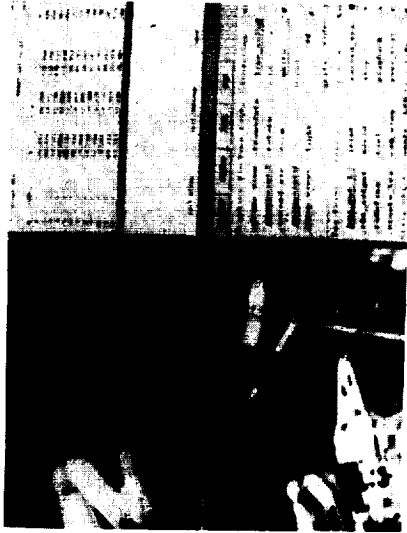
CALIBRATED VIRTUAL ENVIRONMENT FOR ADVANCED TELEOPERATION
JPL-to-GSFC Time-Delay Operations for Simulated HST Platform Repair

(time delay remote video with calibrated 3-D graphics overlay)

(robot operator's multi-media display during task)

ADVANCED TELEOPERATION WORKSTATION
Dual-Arm Control with Graphics Displays for Task Preview and Time-Delayed Operations

simulated ground-to-remote on-orbit equipment changeout similar to that anticipated for future Hubble Space Telescope servicing: from JPL, having geometrically modeled and visually calibrated the "remote" GSFC robot site, we teleoperatively detached and remounted an ORU. The motion planning and execution, both in free space and guarded-contact, were generated by pure teleoperation, with accuracies of millimeters over a work volume of several meters cubed.

COMMERCIAL MARKETS

The ability to calibrate and animate a virtual environment with respect to actual visual robotic workspaces appears to have significant applications potential. As one example, in the area of medical robotics, it suggests a number of possibilities for computer-guided stereotaxic procedures, microtelerobotic surgery, telesurgery proper (actual remote surgical theatres), also multisensory data presentation and visualization. And of course, calibrated VR seemingly is a key ingredient in planning and executing telerobotic operations in remote scenarios subject to either time delay and or partial viewing obstruction. To this end we have joined with Deneb Robotics, Inc., of Auburn Hills, MI, to cooperatively develop a calibrated 3-D graphics-on-video function within their line of 3-D graphics simulation products.

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