MINIATURE TELEROBOTS IN SPACE APPLICATIONS

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ABSTRACT

Ground controlled telerobots can be used to reduce astronaut workload while retaining much of the human capabilities of planning, execution, and error recovery for specific tasks. Miniature robots can be used for delicate and time-consuming tasks such as biological experiment servicing without incurring the significant mass and power penalties associated with larger robot systems. However, questions remain regarding the technical and economic effectiveness such mini-telerobotic systems. This paper addresses some of these open issues and the details of two projects which will be able to provide some of the needed answers. The Microtrex project is a joint University of Washington/NASA project which plans on flying a miniature robot as a Space-shuttle experiment to evaluate the effects of microgravity on ground-controlled manipulation while subject to variable time-delay communications. A related project involving the University of Washington and Boeing Defense and Space will evaluate the effectiveness of using a minirobot to service biological experiments in a space station experiment "glove-box" rack mock-up, again while subject to realistic communications constraints.

I. INTRODUCTION

Humans have a central imperative to explore and to expand their physical domain. Increasingly this is directed to the exploration and eventual colonization of space. However, the hazards of vacuum, high temperature fluctuations, and radiation require humans to live and work in highly protected artificial space environments. The high costs of providing reliable protection for humans in space motivates the use of robotic tools to augment and enhance human activities in space.

In the future, fully automated robots may be utilized to perform coordinated work in space. Near-term activities such as the International Space Station Alpha may also be able to benefit from robots by allowing more activities to be accomplished without placing additional time demands on the limited human crew availability. However, the feasibility of fully automated robots has been limited due to a lack of confidence in Artificial Intelligence technology. Teleoperated robots offer many of the same benefits as automated robots by shifting much of the decision-making intelligence to human controllers. In addition, if the telerobots are controlled from Earth-based control stations, many space activities may be accomplished with little or no orbital crew time requirements. However, the communications requirements for ground-controlled telerobots present difficulties to current and near-term planned space activities.

While it is desirable to be able to do "human-scale" work with human-sized robots in space, the high launch weight, cost and complexity of such systems has limited their near-term viability. In contrast, small robots offer the chance to perform many types of IVA tasks such as environmental maintenance, housekeeping, and the operation of scientific and biological payloads without paying the penalties of higher mass and complexity associated with larger robots. In the future, these minirobots may also be employed for EVA activities such as exterior surface inspection and repair.

Direct-drive actuation may be used to minimize mass, friction, and backlash commonly present in geared drive robot systems. These properties allow open-loop force control to be used, so that delicate manipulation tasks may be done without requiring force sensors on the robot end-effector. However, some questions remain as to the effect of microgravity on the friction properties of precision bearings. These questions must be answered so that satisfactory friction models can be used for open-loop force control in microgravity.

II. BACKGROUND

An important factor of the space environment is the complex nature of the communication links between ground station and this environment. Although in principle, this phenomenon can be simulated, in practise, realistic simulation of the communication link is very difficult to obtain because the existing link technologies were designed primarily for data-logging and involve many interfaces with ground and flight subsystems. Each of these interfaces imposes time delays and bandwidth limitations which vary with time and as a function of the overall mission activities. This is especially true for the Shuttle data links through the TDRSS system of relay satellites. Most operational experience with this data relay system has been during use for archiving (logging) of research data.

Time delays between a human operator and a slave robot have been studied since the sixties. In the original work, Sheridan and Ferrell [1] found that when confronted by time delays greater than about 300 ms., operators adopted a "move-and-wait" control strategy in which he/she performed a task by commanding single simple movements, and waited for visual or other feedback of the results before making another small command. This strategy is very sensitive to the magnitude of the delay and causes dramatically reduced manipulation performance. These and other studies assumed a constant time delay between operator and remote manipulator. Realistic space communication systems will have more complex properties—notably, variable delay, intermittent communication, de-synchronized delays on multiple feedback channels, and bandwidth limitations. These links were designed for archival accumulation of data and have rarely been used for reactive, real-time, decision making and control by a human in the loop.

Friction properties of robot joints in microgravity environments remain uncharacterized. This information is important because it is needed to allow better understanding and control of robot dynamics and

is also needed for precise open-loop force control. In 1-g, bearings in each joint of a serial mechanism are loaded with radial and axial forces which are dominated by a relatively constant gravitational component. In microgravity, this component will be gone and what remains will be a fluctuating force due to manipulator dynamics and contact. Thus micro-surface contact in the bearings will be rapidly changing. This phenomenon cannot be studied on the ground because air bearing tables do not simulate weightlessness in enough dimensions, and floatation tanks supply too much viscous damping.

III. PREVIOUS WORK

STS-RMS System

The Space Shuttle Remote Manipulator System (RMS) — nominally the first robot manipulator in routine space use — has been an essential and extremely useful component of the Space Transportation System. It has repeatedly been used in powerful and unforeseen ways. However, its utility is also limited because it requires a manned mission, and cannot be controlled from the ground. Subsequently, NASA studied the Flight Telerobotic Servicer as a remotely controlled telerobot for servicing satellites in geosynchronous orbit (unreachable by manned missions). However, this project was canceled due to funding limitations.

DLR-ROTEX Experiment

The ROTEX experiment was conducted by Dr. Gerd Hirzinger in May of 1993 [2]. In this experiment, a human scaled, gear driven arm, flown in the Space-Lab D2 was successfully controlled from the Space-Shuttle flight deck, as well as from a ground control station in Germany. The robot was controlled with a "space-ball" hand controller, a device which measures cartesian forces and moments applied by an operator's hand while grasping a ball mounted on the end of a force/torque sensor. The measured forces and moments were used to control the robot's 6-axis cartesian velocities in proportion to the forces applied by the operator's hand. A sophisticated end effector provided an extensive array of end point sensing.

Visual feedback from the ROTEX robot worksite to a ground-based operator was provided via video cameras. However, the presence of substantial round-trip communication delays (5-7 seconds) between the Space Shuttle and the German-based ground station necessitated the use of a graphics simulation system which provided the operator with a simulated real-time view of the remote worksite to facilitate robot operations. Command sequences generated by user interaction with the graphics simulation system were sent up to the ROTEX robot for a later execution.

The ROTEX experiment has generated significant excitement for the potential of space teleoperation, but does not address the high cost and low mission frequency issues associated with large bulky space

robots. A significant new initiative is the ETS-VIII, a Japanese satellite exclusively dedicated to telero-botics experiments [3]. This project is scheduled for launch in 1997.

UW Mini Direct Drive Robot

The University of Washington has recently developed a prototype, 5-axis, mini direct drive robot [4]. The robot (Figure 1) has an overall length of 10 cm and a workvolume of 10 cm^3. It has 5 motion axes

Figure 1: University of Washington Mini Direct-Drive Robot

giving complete freedom to position and orient an axially symmetric tool within the manipulator's joint limits. Analog optical position encoders give positioning repeatability to 1 micron at the end-point. The design makes use of flat coil actuators taken from miniature hard disk drives for very low friction levels, absence of torque ripple, and design flexibility [5]. The current prototype uses actuators from 5 1/4", 3 1/2", and 1.8" disk drives to provide a range of masses and torque capabilities for the various joints in the mechanism. This prototype has already been used in teleoperation tasks that manipulate objects ranging from 5mm to 80μ m in size.

IV. MICROTREX

Objectives

The Microtrex (Micro Telerobotic Experiment) project proposes to use a small flight telerobot in low earth orbit to perform ground-controlled telerobotics experiments. Microtrex will have two primary experimental objectives: First, mathematical models of human/machine system performance [6,7,8,9,10] which have been extensively developed and tested in ground experiments must be calibrated for actual flight operations. Many aspects of the flight environment, such as the detailed characteristics of the con-templated communications channels, have not yet been simulated on the ground.

Secondly, Microtrex will obtain data from which a model of robot joint friction in micro-gravity can be constructed. These factors, unique to the space environment, must be studied with a flight experiment

before planners can guarantee successful performance of manipulation tasks involving contact with rigid objects.

Finally, we intend to make Microtrex a motivational and educational experience for children to encourage and prepare them for study in engineering and science. MicroTrex will include a live interactive video link with elementary and secondary schools to create a motivational and educational experience for children.

Experiment Description

The Microtrex experiment will consist of a flight module and ground station. The Microtrex flight module will consist of the mini-direct-drive manipulator, a control computer, three CCD cameras, and a task board for experimental manipulation. All manipulation experimentation will take place within the fully enclosed flight module. The task board will be mounted within the work volume of the flight module manipulator and will contain several experiments designed to resolve the technical uncertainties described above. First, in order to measure micro-gravity friction characteristics, a surface of controlled hardness and smoothness properties will be provided for constant force and controlled sliding contact tests. Second, to test system capabilities in more application related tasks, and measure operator performance, a peg-in-hole task will be provided. The peg will be held in a restraining fixture, grasped by the manipulator, and inserted into two holes with different tolerances. To be consistent with previous ground studies (e.g. [6]), tolerances of 5% and 0.05% (clearance over diameter) will be used. Finally, additional modules will be included in the task board to perform biotechnology related demonstration tasks. These experimental tasks will allow in depth model calibration for a wider variety of end-user application elements.

The launch carrier for this experiment has yet to be chosen, but will most likely be the STS with the experiment mounted in a cannister in the Hitchhiker G or M configuration. A mock-up of this flight configuration is shown in Figure 2. In this case, two downlink channels (1200bps and 1.4Mbps) and a single uplink channel (1200bps) will be available for communication. This bandwidth will be sufficient for the proposed experiment. However, latencies will be severe (2-4 seconds, variable) due to the TDRSS system. Since the majority of the data bandwidth is required for the video downlink, one option being considered is a direct radio line-of-site downlink from the top of the GAS cannister. This places some additional constraints on Shuttle orientation. If available, the direct radio link will have very low latency but will require tracking antennae on the ground and intermittent operation. To make maximum use of whatever communication link is chosen, we will incorporate data compression for the returning sensor information from wrist force torque sensor and video cameras.

Figure 2: Mock-up of Microtrex flight module in Space Shuttle Hitchhiker configuration.

During experiment operations, an operator situated at the ground station will send commands to the flight module using a multi-axis hand controller. These commands will consist of a data stream of incremental motion commands in the six axes (x, y, z, roll, pitch, yaw) relative to a coordinate system on the flight module task board. The operator will also command the manipulator into a pre-planned sequence of tasks designed to test remote manipulation capabilities and measure joint friction in micro-gravity.

Three CCD cameras will image the end effector and task board of the flight module. Their signals will be compressed and sent back to the operator along with a stream of force and position information. The operator will view the operation using the downlinked video signals, and also be able to view a realistic real-time computer animation of the manipulator from any desired angle.

In order to resolve the friction uncertainty, the Microtrex robot manipulator will be equipped with a micro 6-axis force-torque sensor either at the wrist or in the task board. During contact tasks, contact forces and torques will be both measured by the wrist sensor, and calculated from the joint actuator torques. The difference between the two will be due to the friction. By measuring the difference between actuator and wrist sensor force/torque signals during contact, and transforming that back to the joints via the transpose of the Jacobian matrix, a measurement will be obtained of the joint friction.

Data Analysis

The Microtrex experiment will be the culmination of at least a decade of ground studies in the performance of human-in-the-loop teleoperation systems [11,12]. These and other studies have yielded extensive performance data on ground teleoperation both with and without simulated time delays. Performance of a variety of tasks has been extensively analyzed through a variety of mathematical measures such as completion time, sum-of-squared contact force, RMS force, and observed error rate. From this extensive database, analytical models have been devised through which performance can be estimated on new tasks before experimental teleoperation. One such model is the Hidden Markov Model of human-machine task performance [9] which can derive completion times, and contact force signatures from engineering descriptions of tasks.

However, none of these models has been calibrated against actual space flight. A central aim of the Microtrex experiment is to obtain calibration of model parameters for the unique conditions of microgravity and the complex conditions of orbital communication links. All of the Microtrex proposed experiments would be performed on the ground using the control station, ground prototype manipulator, and a simulated time-delay communication link. The results of the Microtrex experiment will be calibrated analytical models of human-machine performance based on previously developed Hidden Markov Model methodologies and software. This software package will enable a mission planner to design a model for his/her contemplated application, and predict human-machine performance of a telemanipulation system.

Existing work on friction in robot manipulators has focused on a stationary model consisting of three components: stiction, Coulomb friction, and viscous friction. Although these models are difficult to identify with great precision, in the 1-g environment, adequate results have been obtained to justify a stationary model - that is one which does not vary with time [13]. Results from the friction testing component of the experiment will be analyzed to develop a new model which can quantify possible discontinuous, nonstationary friction behavior.

V. SPACE STATION BIOMEDICAL RESEARCH

Many space station research activities will require significant amounts of object manipulation activities. Many of these steps require delicate, high-accuracy motions with small glass "pipette" tubes in order to pick and place small fluid samples or objects floating within small fluid samples. Human crew can perform these activities but current estimates of crew time availability show that only about 2 hours of crew time will be available per day to service all space station experiments after all other required activities such as housekeeping, maintenance, etc. have been accomplished.

A small, ground-controlled telerobot could be mounted within a space-station "glove-box" rack to service multiple experiments without requiring significant human crew interaction. We are working with

Boeing Defense and Space Company to develop a "glove-box" robot for experiment servicing using ground-controlled teleoperation. The robot will be mounted on a mobile platform which allows it to be positioned in front of various experiments in the glove box that require servicing.

During the first stage of this project we are integrating the existing 5-axis manipulator into a Space Station glove-box. Figure 3 shows a mock-up of this configuration using a ~1m wide glove-box. Control
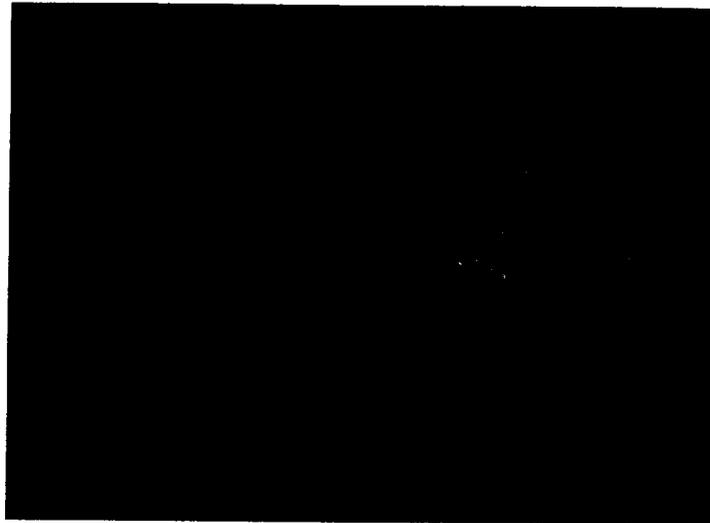
Figure 3: Mock-up of Space Station "glove-box" with mini direct-drive robot positioned for servicing biomedical experiments.

of the robot from across the country will be demonstrated between our laboratory (Seattle, WA) and Boeing (Hunstville, AL) via an internet connection. The eventual goal is to allow individual experiment PI's to service their own experiments by "driving" the robot from their own offices anywhere in the world via internet connections.

A secondary challenge is the development of an efficient teleoperation communication protocol that maintains safe operating conditions at all times in the face of significant communication errors and disruptions. We have developed preliminary versions of this protocol [14] which have already been used for teleoperation tasks with force feedback over internet links between sites as distant as Seattle, USA and Padua, Italy.

VI. CONCLUSIONS

Miniature robot manipulators have the potential to make a significant contribution to both future and near-term space activities. Ground-controlled manipulators can significantly reduce crew time requirements for experiment servicing tasks on the Space Station. While some important technical challenges remain, significant inroads will be made in the near future. We have described experiment activities

which will address some of these concerns and help promote the use of miniature robots in future space activities.

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