ABSTRACT

The National Aeronautics and Space Administration (NASA) Space Station Program marks the beginning of a new era in space utilization and habitation. Extensive use of remote manipulation and robotics to reduce astronaut extravehicular activity is expected. Emphasis on teleoperator technology in early space station phases, followed by growth of autonomous robotics capabilities, is planned. A new telerobot concept has been developed at Oak Ridge National Laboratory (ORNL), under NASA Langley Research Center sponsorship, to address the technical needs of both teleoperations and robotics for these future NASA programs. The concept is based on traction drives, redundant kinematics, modular construction, and a state-of-the-art distributed, hierarchical control system.

INTRODUCTION

The NASA Space Station Program marks the beginning of a new era in space utilization and habitation. A major factor in this program will be the need for significant levels of equipment assembly, operation, and maintenance in the hazardous environment of space. Many of these activities will require human-like dexterity outside of the controlled environment of the human-occupied modules. To meet the many challenges of this new era, expanded use of remote teleoperation and robotics by NASA is expected. Reliance on teleoperations during the early phases of the Space Station Program is planned. As supporting technology is developed and demonstrated, operations will evolve toward use of autonomous robotics techniques. It is expected that the underlying advanced electromechanical, sensory, and control technologies of these future systems will improve NASA mission safety and productivity while stimulating significant advancements in industrial robotic technologies for application in U.S. industry.

The space shuttle Remote Manipulator System (RMS)\(^2\) has demonstrated the value of teleoperation technology in space. A vast array of tasks including the capture, repair, and redeployment of satellites has been demonstrated. The large physical size of the RMS makes it suitable for manipulating sizable structures and objects. Nevertheless, this large size accompanied by slow speeds and relatively flexible links limits its dexterity for the small volume tasks associated with equipment assembly and repair. Smaller, more dexterous telerobotic systems will be required to expand the work range of space telerobots to perform more complex tasks such as satellite maintenance, space construction, and vehicle refueling operations. The goal for development and application of space telerobotic technology is to increase astronaut and system safety, productivity, and flexibility through reduction of space station-related extravehicular activity (EVA) time.

DESIGN APPROACH

The overriding design goal for the space telerobot development efforts by NASA, Langley Research Center, and ORNL is the development of a manipulation system capable of performing a range of manipulation tasks presently accomplished.
by astronauts during EVA, as well as a significant portion of tasks planned for the Space Station. The dexterity of astronauts during EVA is attenuated significantly by the protective suit with pressurization. A catalog of special tooling has been developed to deal with the reduced manual dexterity of suited astronauts. In addition, fatigue is a concern when humans perform tasks while suited in protective clothing. Fatigue can result in reduced productivity and potential for mistakes. Nevertheless, the suited astronaut has unmatched flexibility and adaptability when operating in unstructured environments. From a NASA viewpoint, the ability to deal with the unexpected is probably the strongest attribute of the EVA astronaut. This capability must be provided in space telerobots systems through robust teleoperator performance and effective operator interfacing. Another way to state this important feature is that the capabilities of a space telerobot must match the dexterity of a suited astronaut performing EVA to the extent practical in today’s technology.

Teloperated force-reflecting servomanipulators are presently the most efficient means of performing non-repetitive remote maintenance in unstructured terrestrial hostile environments. ORNL has, over the last ten years, maintained the most extensive R&D program for these manipulation systems in the United States. The robotics field has significantly impacted manufacturing automation efficiency, quality, and flexibility. These two technologies utilize differing manipulation design features which are optimized for their respective application and modes of operation. ORNL has chosen to merge these two technologies to provide the best features for good teleoperation while providing a good foundation for the growth of autonomy. This approach is shown in Table 1. The most important design and performance goals for the space telerobot are as follows:

1. Force-reflecting replica kinematics under teleoperated control for demanding operations requiring a "sense of feel."
2. Good foundation for sensory-driven robotic operations with position or force control for planned repetitive tasks and growth of autonomy.
3. Redundant manipulator kinematics for movement around local obstacles.
4. Dual-arm system for two-handed tasks and tooling.
5. Local control intelligence and high bandwidth communications links for flexibility and system expandability.
7. Reconfigurable in physical size and kinematic arrangement to increase task applicability.
8. Modular structure for high maintainability and reliability.

MECHANICAL DESIGN

A compact and versatile wrist mechanism has been implemented on the Advanced Servomanipulator at ORNL. This compact wrist mechanism provides pitch, yaw, and roll motions with orthogonal and intersecting axes to orient the end-effector. Robot wrists are very difficult to design because of their required compactness and wide range of motion. A variation of this design using only the pitch and yaw motions has been implemented at the shoulder, elbow, and wrist joints of the space telerobot arm (shown in Figure 1) for a simple, kinematically redundant manipulator. The addition of a distributed wrist roll at the output provides the seventh degrees-of-freedom and completes the kinematic sequence. The arm segments are kinematically identical; they can be designed as relatively common subelements with remotely operable interfaces. These

Figure 1. ORNL space telerobot concept
Table 1

<table>
<thead>
<tr>
<th>SPACE TELEROBOT CRITERIA DEVELOPMENT</th>
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<tbody>
<tr>
<td>Good force-reflecting teleoperator</td>
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<tr>
<td>End-effector speed ( \geq 36 \text{ in./s} )</td>
</tr>
<tr>
<td>Friction 1 to 5% of capacity</td>
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<tr>
<td>(at expense of increased backlash)</td>
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<tr>
<td>Medium to low backlash</td>
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<tr>
<td>Replica master control</td>
</tr>
<tr>
<td>1- to 2-in. deflection at full load</td>
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<tr>
<td>6 DOF(^{a}) and end-effector</td>
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<tr>
<td>Bilateral position-position control for force reflection with man in the loop</td>
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<tr>
<td>Relatively low inertia for minimum fatigue</td>
</tr>
<tr>
<td>Kinematics approximately manlike</td>
</tr>
<tr>
<td>Accuracy and repeatability not important</td>
</tr>
<tr>
<td>1:4 to 1:10 capacity/weight ratio</td>
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<tr>
<td>Universal end effector</td>
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**TELEROBOT**

End-effector speed \( \geq 36 \text{ in./s} \)
Friction close to teleoperator, much lower than robot
Backlash close to robot, much lower than teleroperator
Replica master control preferable, joysticks and autonomy research possible
0.05-in. deflection at full load
7 DOF\(^{a}\) plus end effector
Bilateral position-position control for force reflection
Low inertia compared to robots
Manlike kinematics for dexterity in teleoperation
1:4 capacity/weight ratio
Universal interface for NASA end-effector research
Capacity of 20 lb continuous, 30 lb peak
Arm cross section to reach inside 6-in.\(^{a}\) opening

\(^{a}\)Degrees of freedom

Interfaces allow easy replacement of failed modules, reduce spare parts inventories, and allow reconfiguration with alternate link segments for unusual tasks. Manipulator subelement commonality should significantly reduce replication costs.

The seventh joint, to be used as a translational degree-of-freedom, increases the volumetric coverage of the translational joints and allows the telerobot arm to be reconfigured to approach the worksite from a number of directions. These multiple working configurations become useful when manipulation in cluttered environments is required. Additionally, the reorientation of the lower arm allows presentation of the wrist optimally for force control. The space telerobot manipulator joint module is composed of dual brush-type dc motors, traction-drive speed reduction, traction differentials, and a yaw-pitch output as shown in Figure 2. Three modules with electrical interconnections are grouped to form an arm. In a microgravity environment, the major difference between modules will be the reduction ratio required to match the
Figure 2. Telerobot joint differential motor speed and capacity requirements to the joint parameters for each arm link.

CONTROL SYSTEM

The development of control system architectures for intelligent telerobotic systems is the subject of research at several NASA centers and at the National Bureau of Standards (NBS). The basic concepts discussed here are compatible with the much more detailed concepts for the NASA/NBS Standard Reference Model for Telerobotic Control System Architecture (NASREM) and the NASA/Johns Hopkins Applied Physics Laboratory Run-Time Control System.

The control system of a telerobot is a critical element of its basic performance and of its integration with other spacecraft functions. In this work, a control system architecture has been conceived that will allow the spacecraft telerobot to incorporate technological advances which can be integrated into external computer systems. The control architecture must support both robotic operations and teleoperations with real-time human control. A block diagram of the major functions within the control system is shown in Figure 3. This architecture is an extension of the control systems developed for the M-2 and ASM systems by ORNL. A brief discussion of each functional block follows.

Local/Remote Servocontrol

This block provides closed-loop control at the manipulator joint level. Input commands include position, speed, and torque. Position, joint torque, and joint velocity are fed back from each joint. Outputs of the block are drive signals to the joint amplifiers. Secondary functions of this element include overload monitoring and protection and system diagnostics.

Human-Machine Interface Input/Output Processing

The human-machine interface (HMI) of a telerobot includes control devices for operating the manipulator as well as a complement of displays and controls associated with general operation of the system. The HMI also includes the displays for the remote viewing used in teleoperation. A new approach to display and viewing integration involves the incorporation of graphic overlays (as done on broadcast television) for control displays. It is expected that a hand-held control pendant, replica master controllers, and voice input/outputs will be components of a system emphasizing operator flexibility and comfort.

The HMI input/output processor determines that a command is valid and posts command information into the common memory for action. This type of HMI concept for telerobotic operations is compatible with preview and control for situations involving long data communication delays (e.g. operation beyond line of sight).

Task Planning and Diagnostic Processor

This block represents a supervisory function which monitors the database for the system condition and generates status information to be used by the HMI. In operational scenarios where long time delays exist, this element plans intermediate paths and suggests decisions based on the supervision of the operator. In earth-based systems, time delay makes task planning more critical. The portion of the system dedicated to task planning is anticipated to be larger and more powerful. It works in coordination with the remote path planner to reduce the bandwidth and frequency of communications.
Figure 3. Telerobot control system architecture

Local/Remote Common Memory

The telerobot control architecture utilizes the established notion of a common, or global, memory to serve as a read/write "blackboard" which ensures the accuracy and temporal synchronization of data transfers between the local and remote subsystems.

Local/Remote Communication Processors

These elements handle and check communications in the form of data transfers between the local and remote common memories. During times of low data communications, the computational resources of the remote processor may be used to assist the planning and diagnostics element.

Path Planner and Sensory Transformer

This element transforms sensory information (e.g., from six-axis wrist force sensors, vision sensors, proximity sensors, etc.) into joint space coordinates. It will also use intermediate path points and operating modes to generate inputs for remote servocontrol processing. By using intermediate path set points and dividing them into fine-grain path set points, the communications bandwidth can be greatly reduced.

World Sensory Feedback System

This system interfaces a series of sensory systems to the common memory and allows feedback of global information that is necessary for higher levels of control. The system applies to autonomous operations. Preprocessing of vision information and analog information scaling are accomplished in this element.

Implementation

There are many ways to implement the telerobot control system architecture which has been described. Current work in the development of a prototype uses fairly standard hardware arrangements. The system will be entirely digital using 32-bit microprocessors (e.g., the Motorola MC68020) and standardized bus structures (e.g., the VME). These building blocks will be used to create computational islands at both the local and remote subsystem. Each island will be comprised of one or more VME racks with multiprocessors (tightly coupled on the VME bus). Multiple racks will be interconnected through a local-area network type serial data highway. The local and remote subsystems will be interconnected through a very high speed bidirectional communications link which will accommodate at least 10 Mbit/s bidirectional data communications. This hardware arrangement is typical of advanced robot and manufacturing control systems. The vast majority of software will be developed in high-level languages like C, Pascal, Forth, and ADA.

Even though today's 32-bit microprocessors provide VAX-level computation in single-board computers, as the telerobot system evolves toward increased robotic and autonomous functions, more advanced computer architectures will be required. Advanced parallel machines such as the NCUBE hypercube will be required to perform complex calculations on massive amounts of sensor data. It is believed that the
proposed implementation scheme will readily accommodate such advancements.

There are, of course, many opportunities for electronic innovation in the implementation of the control system. The potential advantages of using applications-specific-integrated circuits (ASIC's) are being studied. ASIC chips may facilitate substantial simplification of complex cable routing requirements by permitting some electronic processing to be physically integrated into the telerobot manipulator structure. For this space application in which periodic component (at the board level) replacement is feasible, special radiation-hardened electronics will probably not be required to achieve acceptable operating intervals.

**STATUS**

Detail design and fabrication of the first prototype of the ORNL space telerobot system has been initiated. This effort will produce the first demonstration of the concept with two force-reflecting master and slave arm pairs with the associated control system. It is planned that the prototype system will be initially operational in late March of 1988. Based on successful performance of this prototype unit, engineering units will be fabricated and supplied to NASA telerobotics development laboratories for ground development of control hardware, software, and sensors as well as for research into implementation of autonomous systems. In order to support basic mechanical design and controls development, dual master and slave joint hardware simulations are planned. The first of these bench-top units, shown in Figure 4, has been completed and is in initial mechanical testing to quantify basic joint parameters.

**REFERENCES**


