# TELEROBOTIC TECHNOLOGY FOR NUCLEAR AND SPACE APPLICATIONS

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## ABSTRACT

Telerobotic development efforts at Oak Ridge National Laboratory are extensive and relatively diverse. Current efforts include development of a prototype space telerobot system for the NASA Langley Research Center and development and large-scale demonstration of nuclear fuel cycle teleoperators in the Consolidated Fuel Reprocessing Program. This paper presents an overview of the efforts in these major programs.



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## I. Background

Oak Ridge National Laboratory (ORNL) has been involved in extensive teleoperator and telerobotic development for the last ten years. Programs currently in progress include prototype development for a space telerobot and development and demonstration of teleoperators for nuclear fuel cycle applications. Extensive staff expertise and experimental telerobotic hardware capabilities have been developed at ORNL and these resources are being applied to diverse national research needs.

## II. Teleoperator Development and Demonstration for Nuclear Fuel Cycle Applications

The Consolidated Fuel Reprocessing Program (CFRP) at ORNL is developing advanced techniques for remote maintenance of future U.S. nuclear fuel reprocessing plants. These developments are based on the application of teleoperated force-reflecting servomanipulators for dexterous remote handling with the operator outside the hazardous area. Employing highly dexterous manipulation will increase maintenance system capabilities, thereby reducing reprocessing plant mean-time-to-repair. In addition, the use of remote maintenance techniques will decrease plant personnel radiation exposure. These developments fully address the nonrepetitive nature of remote maintenance in the unstructured environments encountered in fuel reprocessing.

The CFRP has been active in advanced teleoperations development for more than eight years. Development has been stepwise with two major maintenance systems being designed prior to initiating the current efforts. The first large-volume servomanipulator-based maintenance system installed in the Remote Systems Development Facility was equipped with a pair of TeleOperator Systems SM-229 servomanipulators mounted on an overhead telescoping tube transporter with television cameras mounted on positioning arms. Efforts in this facility included studies of man-machine interface issues as well as manipulator joint duty cycles.[1,2] The second large-volume system is installed in the Remote Operations and Maintenance Demonstration Facility. The maintenance system in this facility is based on a pair of Central Research Laboratories Model M-2 servomanipulators mounted on an overhead telescoping tube transporter with television cameras on positioning arms and an integral 230-kg hoist.[3] The M-2 system was the result of cooperative development efforts of Central Research Laboratories and ORNL and was the first successful implementation of digital control techniques for a force-reflecting servomanipulator.[4] Current efforts in the Remote Operations and Maintenance Demonstration Facility involve remote maintenance checkout for prototype reprocessing equipment. In addition, detailed testing of various technical issues in the application of remote manipulator systems is carried out. Recently this facility has been used to perform preliminary studies of remote teleoperation with high dexterity manipulators for space and military applications.

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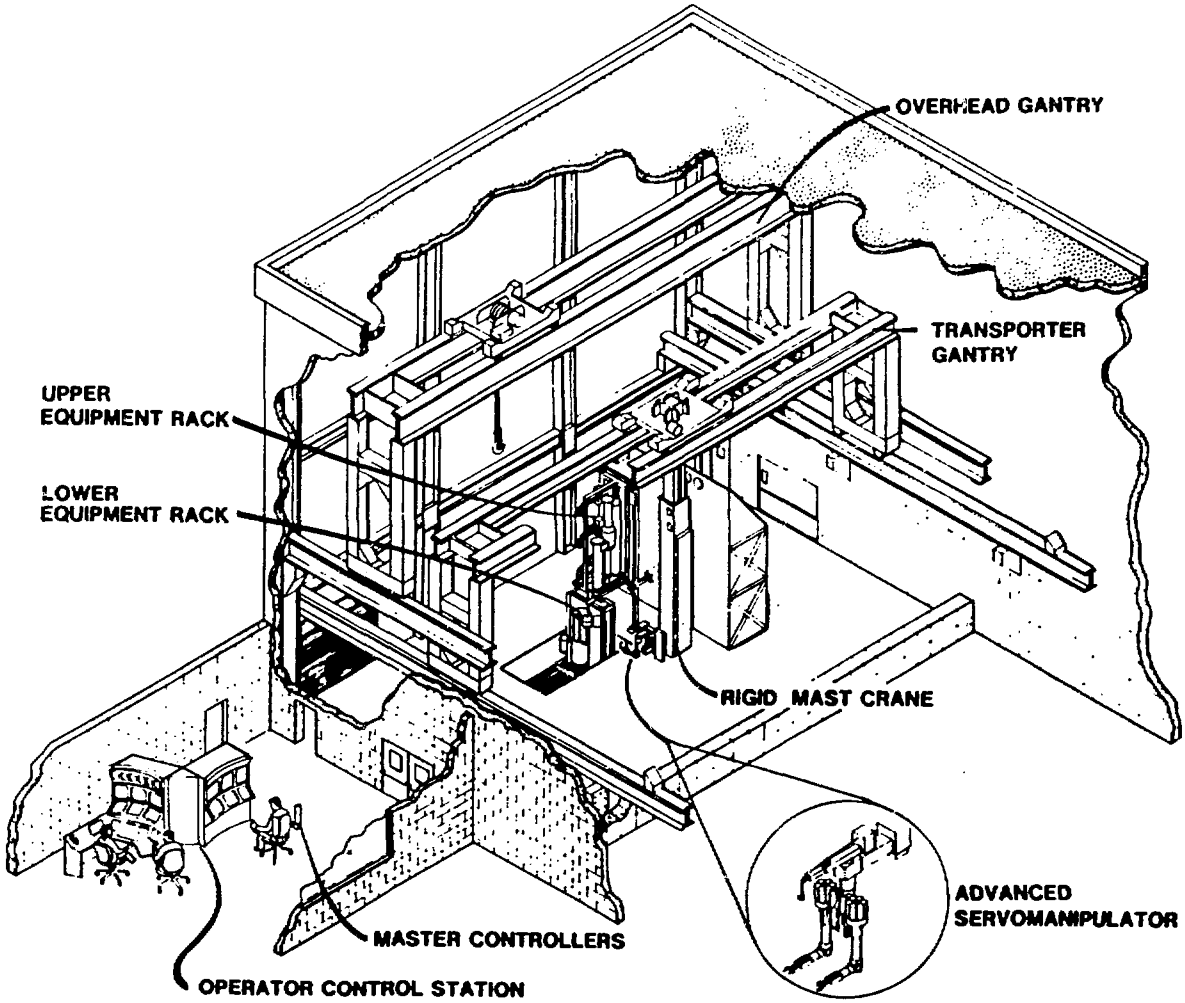


Fig. 1 Advanced Integrated Maintenance System

The third prototype remote handling system developed for reprocessing applications developed is the Advanced Integrated Maintenance System (AIMS). This system is a prototype for maintenance systems in future nuclear fuel reprocessing plants. The AIMS system, shown in Fig. 1, incorporates all the subsystems required for large work-volume reprocessing applications. The key feature of the AIMS is use of the advanced servomanipulator slave arm force-reflecting servomanipulators designed for modular remote maintainability.

## Advanced Servomanipulator Slave Arms

The advanced servomanipulator (ASM) slave arms were developed specifically for the extremes of a reprocessing environment. Nuclear radiation and surface contamination levels are very high in a reprocessing cell and the atmosphere contains nitric acid vapors. Ultimately the slave manipulators must function reliably in this environment.

A major goal has been to modularize the slave arms to permit repair by other ASMs. Previous designs for bilateral, force-reflecting servomanipulators have utilized tendon drives for reduced inertia and friction but these drives are very difficult to repair. Extensive decontamination followed by lengthy contact maintenance is required for repair of tendon drives used in reprocessing applications. The ASM slave arms have been designed with all gear and shaft drives in order to allow segmentation of the arms into modules for remote handling. The slave arms were designed for 23-kg capacity in any orientation, end-effector maximum no-load velocities in excess of 1.0 m/s for each individual joint, and low no-load backdriving torque (~5% of capacity) for force-reflecting operation with bilateral, position-position servocontrol. The first two prototype arms were designed and fabricated at ORNL (see Fig. 2). The arms have six degrees of freedom for generalized positioning in space, with a grip as the seventh degree of freedom. An anthropomorphic (man-like) kinematic arrangement was employed to provide horizontal reach capabilities in constrained areas. The unique four-degree-of-freedom wrist has pitch, yaw, and output roll motions with intersecting axes. The arm is composed of 15 individual modules sized for handling by another manipulator. This modular design is accomplished by the use of precision gear and shaft drives throughout. In addition, electronic counterbalancing is employed to eliminate balance weights and thus reduce the arm cross section. A detailed description of the ASM slave arms can be found in ref. 5.

## Master Controllers

The manipulator control input device is critical in terms of the work task efficiency of the overall teleoperator. The ASM controller is a kinematic replica master configuration which provides very transparent control of all manipulator joints. The master arms for the ASM were designed for operation in the human-occupied control room and did not require the modularity provided in the slave arms. Stainless steel cable drives were employed for all joints below the shoulder in order to minimize friction and inertia. The master controllers were designed for a reduced 6-kg capacity in any orientation, end-effector maximum no-load velocities in excess of 1.0 m/s for each individual joint, and low no-load back-driving torque (~4% of capacity) for force-reflecting operation with bilateral, position-position servocontrol. The dual-arm prototype master controller is shown in Fig. 3. Mechanical counterbalancing is used on the master for reduced drive friction compared to the electronic counterbalancing of the slave arms. A detailed description of the master controller arms can be found in ref. 6.

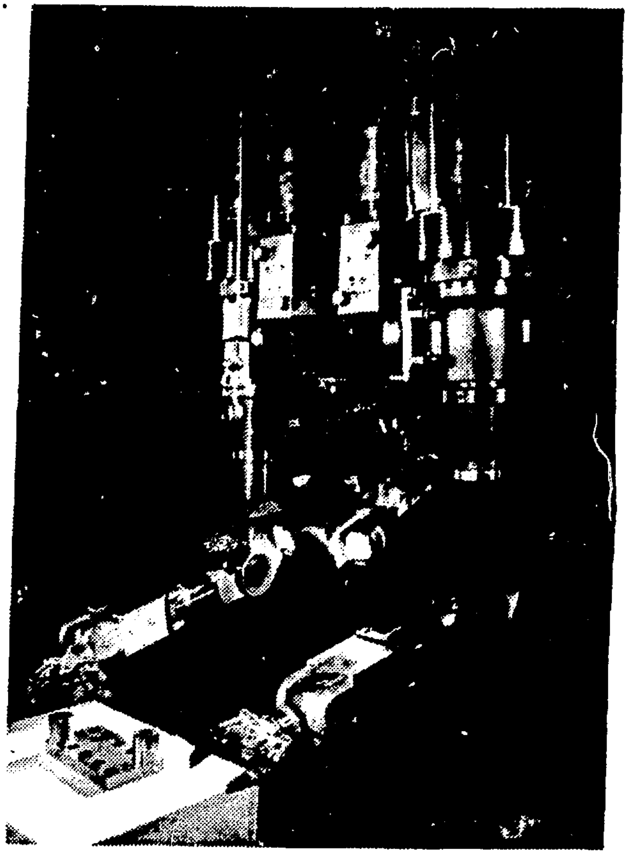

Fig. 2 Advanced Servomanipulator

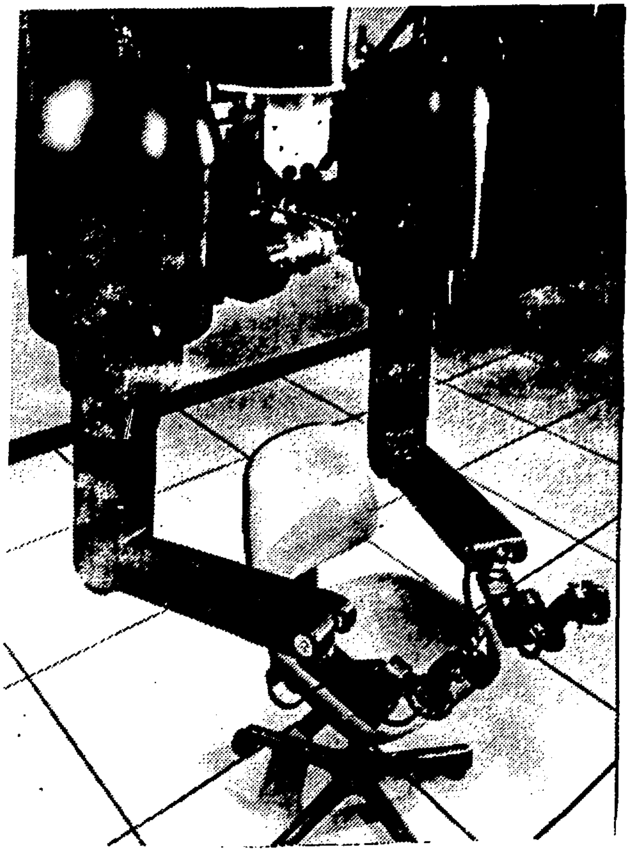

Fig. 3 ASM Master Controllers

Transporter and Interface Package

The ASM slave manipulators are positioned in the three-dimensional workspace using an overhead bridge, carriage, and mast system. An adaption of an industrial rigid mast crane has been used for the AIMS transporter system. Rigid mast cranes have been used extensively in industry for many years for material handling and automated warehouse storage and retrieval systems. The initial prototype for AIMS is a gantry bridge version (Fig. 1). The rigid mast section is mounted on a rotating turntable supported by a large diameter bearing and an external gear to provide 370° rotation of the mast.

The interface package is remotely detachable from the transporter and provides the balance of the in-cell remote maintenance system. The interface package supports two overhead television cameras with lights on four-degree-of-freedom positioners, a center camera with lights on a two-degree-of-freedom positioner, mounts for the ASM slave arms, and a 460-kg capacity auxiliary hoist with extend/retract motion. A rotation drive about the interface package centerline is also provided for ease of in-cell positioning in arbitrary orientations.

Operator Control Station

The operator control station design for AIMS benefitted extensively from the Remote System Development Facility and Remote Operations and Maintenance

Demonstration control station operation. In addition, the design is based on the extensive program of human factors research in teleoperation which has been in progress at ORNL for seven years. The AIMS operator station,[7] shown in Fig. 4 is based on a two-operator team approach to control maintenance operations and the use of flexible graphic display-based controls. Good inter-operator communication, both visual and verbal, is essential. The manipulator operator, shown on the right in Fig. 4, is responsible for performing dexterous maintenance operations using the master controllers with television viewing. The operator has three color graphic displays for status information and menu selection using a master controller grip-mounted cursor control. The secondary operator, stationed on the left side, is responsible for control of the transporter, a large overhead 20-ton crane, television camera positioning, control station displays, and overall maintenance supervision. The control room arrangement was designed based on ergonomics principles to cover a wide anthropometrical range, and prior to construction was mocked up and thoroughly tested for ease of use by the required operator population.

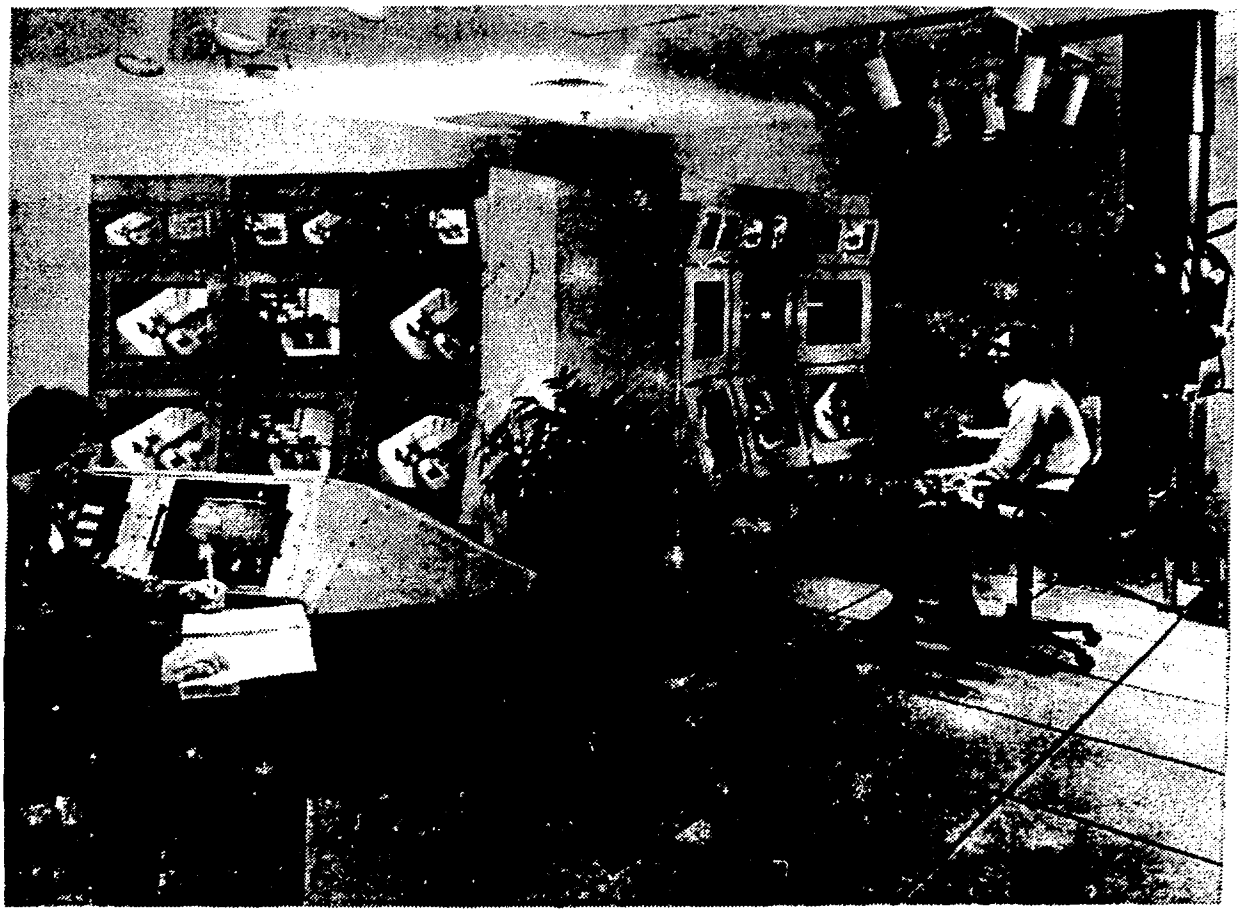

Fig. 4 AIMS Control Room

Control System

Control of the AIMS is a sizable challenge due to the breadth of the requirements. The control system must provide for 30 bilateral, force-reflecting joints, which require updating at 100 Hz. In addition, 56 nonforce-reflecting drives, more than 100 discrete outputs, 6 graphics displays, 21 television displays, and 2 separate operator control stations must be controlled. This problem has been solved by a hierarchical building block approach (see Fig. 5) utilizing an industry-standard Multibus backplane (IEEE-796) for expandability and flexibility. Single-board Motorola 68000-based computers for control calculations and Megalink boards for communications are used throughout the system. Input/output and special devices are chosen to meet individual subsystem requirements. All software modules in the system are programmed in FORTH for speed execution in a high-level language environment while providing a good interactive software development environment.

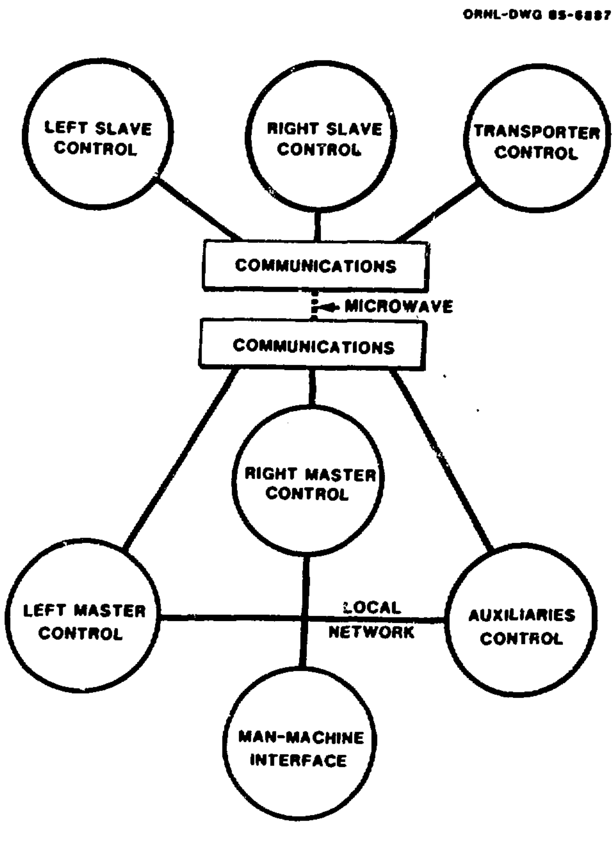


Fig. 5 AIMS Control Architecture

The ORNL has led the world in the development of digital-based control systems for bilateral force-reflecting servomanipulators. The controls for the ASM, based on the hardware described above, are the most advanced of any force-reflecting servomanipulator in existence. Through special software compensation methods, the adverse effects of much higher levels of friction, inertia, and cross coupling of torques on the slave arm have been minimized. In addition, electronic counterbalancing of the slave arms has been achieved without significant adverse effects on force-reflection sensitivity.

## III. Prototype Telerobotics For Space

The NASA Space Station Program marks the beginning of a new era in space exploitation 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 dexterity outside 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.

The principal design goal of the space telerobot development work in progress at NASA Langley Research Center and at ORNL is development of a manipulation system capable of performing a range of manipulation tasks presently accomplished by astronauts during extravehicular activity (EVA), as well as a significant portion of tasks planned for space station assembly, operation, and maintenance. Astronaut dexterity is significantly reduced during EVA by the protective pressure suit. 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 a key attribute of the human astronaut. This level of capability must be provided in future space telerobot systems (through robust teleoperator performance and effective operator interfacing) if they are to have a significant role in space operations. Another way to state this important feature is that the capabilities of a space telerobot should approach the dexterity of a suited astronaut performing EVA to the extent practical with today's technology. In this vein, ORNL developed a dexterous manipulator concept based on related applications in nuclear research and development. The mechanical and control system features of the proposed telerobot concept are described in the following sections.

### Mechanical Design

Robot wrists are very difficult to design because of their required compactness and wide range of motion. A compact and versatile wrist mechanism was developed and implemented on the advanced servomanipulator[5] at ORNL. This compact wrist mechanism provides pitch, yaw, and roll motions with orthogonal, intersecting axes to orient the end effector. A variation of this design using only the pitch and yaw motions has been implemented in the form of similar manipulator elements at the shoulder, elbow, and wrist joints of the space telerobot arm (shown in Fig. 6) for a modular, kinematically redundant manipulator. The addition of a distributed wrist roll at the output provides the seventh degree of freedom and completes the kinematic sequence. The arm segments are kinematically identical; they can be designed as relatively common sub-elements with remotely operable interfaces. These interfaces permit easy replacement of failed modules, reduce spare parts inventories, and allow reconfiguration with alternate link segments for specific task requirements.

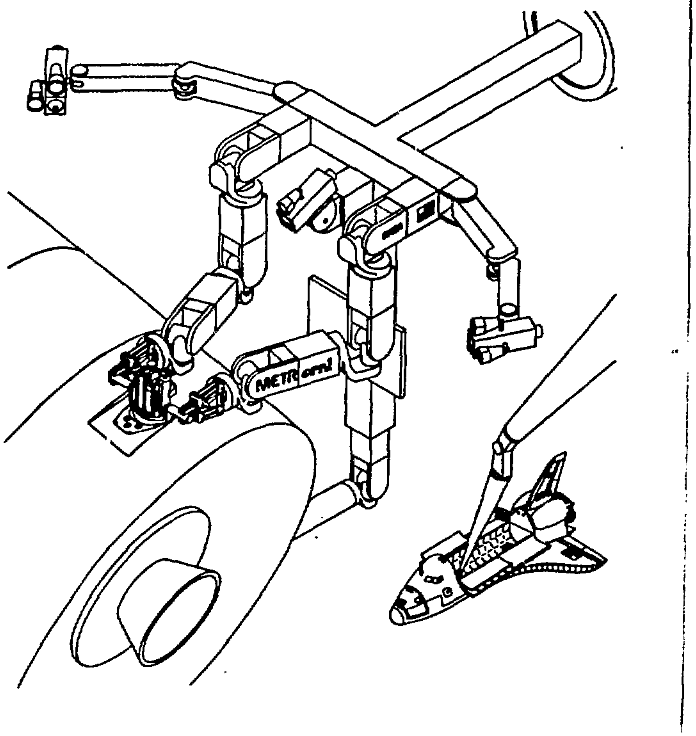

Fig. 6 NASA Langley/ORNL Space Telerobot

The seventh joint, to be used as a translational degree of freedom,[8] maximizes the volumetric coverage of the overall manipulator and allows the telerobot arm to be reconfigured to approach the work site from a number of directions. These multiple working configurations become useful when manipulation in cluttered environments is required. Additionally, the orientation flexibility of the lower arm allows optimal presentation of the wrist/end effector for force control. The space telerobot manipulator joint module is composed of dual brush-type dc motors, speed reduction and traction differentials,[9] and a yaw-pitch output as shown in Fig. 7. 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 motor speed and capacity requirements to the joint parameters for each arm link.

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 space telerobot to incorporate future computer technoloy advances, especially in the area of hierarchical software concepts. The control architecture must support both robotic operations and teleoperations with real-time human intervention. A block diagram of the major functions within the control system is shown in Fig. 8. This system concept is an extension of the control systems developed by ORNL for the M-2 and ASM systems.[10]

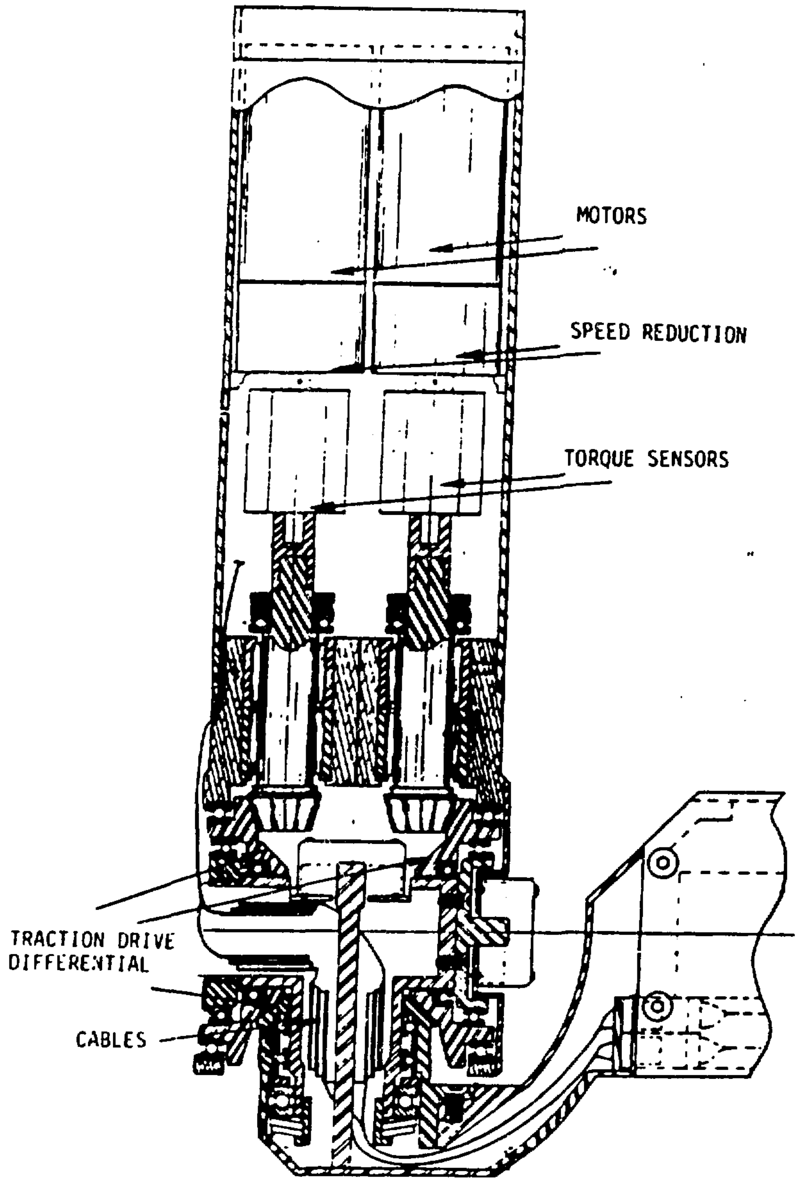


Fig. 7 Space Telerobot Joint Differential

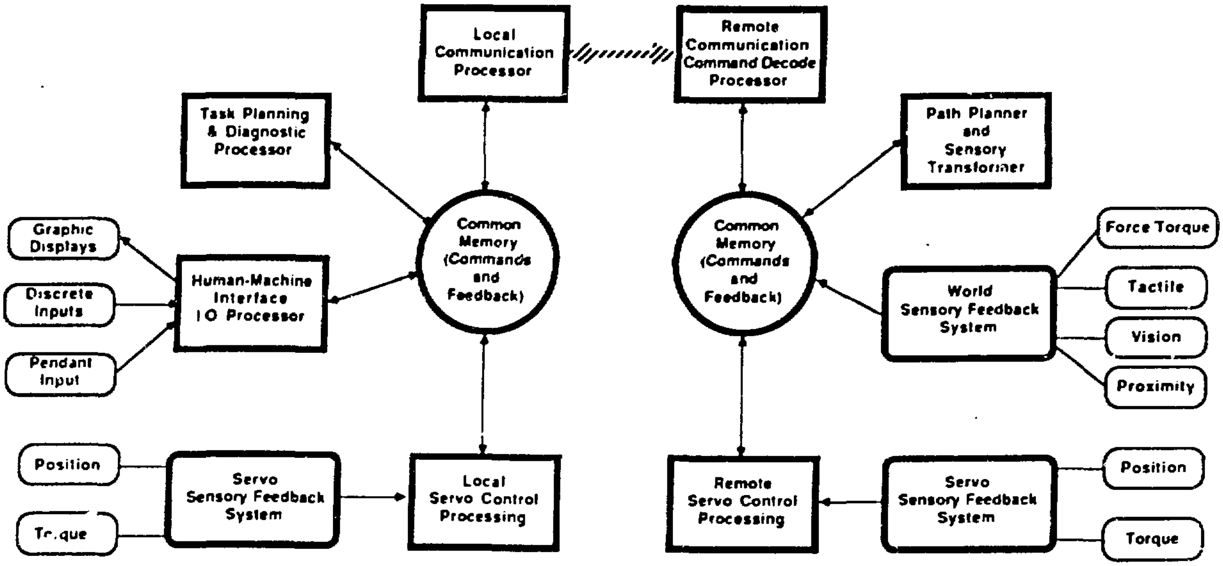


Fig. 8 Space Telerobot Control Architecture

There are many ways to implement telerobot control system architecture and, for performance and cost effectiveness, the prototype will use fairly standard hardware arrangements. The system will be entirely digital, using 32-bit microprocessors (e.g., 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 subsystems. Each island will comprise 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 that 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 the software for this system will be developed in user-selected high-level languages such as C, Pascal, FORTH, and ADA.

Even though today's 32-bit microprocessors provide VAX-level computation in single-board computers, more advanced computer architectures will be required as the telerobot system evolves toward increased robotic and autonomous functions. 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 (ASICs) 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 replacement (at board level) is feasible, special radiation-hardened electronics should 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 a dual arm system consisting of two force-reflecting master and slave arm pairs with the associated control systems. It is planned that the prototype system will be initially operational in April 1988. Based on the 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, a single two degree-of-freedom joint has been designed and fabricated. This assembly will be used in bench-scale experiments to evaluate joint-level servo parameters and control algorithms. A second two-degree-of-freedom joint will be fabricated shortly to allow master-slave operation.

## IV. CONCLUSIONS

Significant progress has been made in recent years in the development of new remote systems technology for nuclear applications. This progress has involved major advances in teleoperations, manipulator design, and human factors engineering of advanced teleoperation.

This nuclear applications work is now being used as a foundation in the development of dexterous manipulation concepts suitable for future space applications such as those associated with the Space Station Program. The NASA/ORNL Space Telerobot System Project is developing a seven degree-of-freedom force-reflecting manipulator that will approximate astronaut EVA capabilities. A prototype manipulator based on this concept is now being designed for ground-based precursor experiments and developments associated with future space missions.

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