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Distributed Control Architecture for Real-Time Telerobotic Operation

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1. Abstract

The emerging field of telerobotics places new demands on control system architecture to allow both autonomous operations and natural human-machine interfacing. The feasibility of multiprocessor systems performing parallel control computations is realizable. A practical distribution of control processors is presented and the issues involved in the realization of this architecture are discussed. A prototype dual axis controller based on the NOVIX computer is described, and results of its implementation are discussed. Application of this type of control system to a replicated, redundant manipulator system is also described.

2. Introduction

The development of the field of telerobotics is presently in its infancy. Driven forward by increasing application demands in space, nuclear, underwater, and battlefield activities, this new area of technology is rapidly expanding. The advent of more powerful and cost effective computing technology has provided solutions to many of the practical problems posed in the development of telerobotic controls. The development of a system that can expand with future technological progress, allow multiple programmers to simultaneously author code, and provide for autonomy as well as human control is the challenge that lies immediately ahead for NASA. To meet these challenges requires an open architecture with parallel processing performance and the ability to be organized in a logical hierarchy for future expansion. Partitioning of such a hierarchy requires that many questions related to performance, expansion path, communications, and software be answered.

The first step that must be taken to partition a telerobotic controller is to define the major control activities and information flow paths/rates that are associated with those activities. A top level listing of the activities that must be performed in a telerobotic controller is given:

1) Servomechanism control.
At the foundation of any telerobotic controller is the subsystem that must close the control loop around the encoder information and the motor drive amplifier to provide stable, responsive operation to input drive commands. Traditionally, robotic controls have utilized position as the input command and have sensed position and velocity information to accomplish closed loop control of joint location. More recently, developments have been made that allow torque control to be performed with servomechanisms. Different modes of operation may be required to optimize joint performance for a given task. This lowest level of control requires loop closure rates from 10 to 1000 Hz depending on the fidelity of control that is desired.

2) Human-machine communications.
The key to flexible and multipurpose telerobotics is the ability of the system interface to be made transparent to the human operator. Efficient operation of a telerobot in unanticipated applications will require that the human have full and natural command of all functions of the manipulation system. Improvements in graphic displays, master controllers, force-reflection capabilities, and viewing methods will be required to improve telepresence efficiency. Computational burdens associated with real-time graphic displays, controller transformations, and system diagnostics can result in slowly responding human-machine interfaces unless proper distribution of computational requirements is accomplished.

3) Sensor integration.

A primary key to successful autonomous operations is the ability to acquire and decipher sensory information from a number of different sensory systems. Acquisition and fusion of vision, tactile, force, and scanning information is computationally intensive. Such sensory information must be available at rates of 1 to 30 Hz depending on the type and quality of the information. Software to extract information from sensory data is being developed by a number of researchers at many institutions to solve specific application problems. Such diverse sensory development activities will conceivably continue requiring a flexible, but well documented sensory communications interface.

4) Activity/motion planning.

Planning is to robotics as the operator is to teleoperation. For reliable robotic operations to occur, the controller must have the ability to intelligently act on high level commands and adjust actions according to information returned from the sensory integration system. The capability to modify actions based on the condition of the environment is the key to developing a broad range of autonomous capabilities with the telerobotic controller. Equally important is the ability of the planner to know when the situation dictates that external human intervention is necessary to circumvent a difficult situation.

5) Internal operational communications/common memory manager.

Sequencing between planned activities and actual movement commands must be accomplished in a failsafe manner. The internal communications manager assures that the data transfers between the servomechanism controllers and the common memory data base occurs in an organized manner to assure that data collisions are minimized. The common memory data base serves as a documentable map of all defined sensory and control data locations. As such, it can provide the ability for a number of software developers to independently work on subsections of the code without requiring an entirely functional system. For long term evolutionary development that involves multiple software creators, the strict adherance to a documented common block of memory will save much time and effort while resulting in a flexible system.

6) External coordination communications.

To allow multiple manipulation elements to interact, it is imperative that an external communications handler be developed to sequence and transfer information from one manipulator memory common block to another manipulator memory common block. Language and communication rates must be delineated in order that the protocol for manipulator to manipulator communications may be determined.

7) Diagnostic handling.

Overseeing all of the activities that occur within the system, there must exist a diagnostic handling system. This system monitors the basic functionality of the system components on its lowest level and approves the general logic of activities on its highest level. This system diagnoses activities from the concrete (temperature, current trips, enables, etc.) to the abstract (collision between manipulators is emminent, tool not located, you are attempting to enter a restricted manipulation area, etc.) and provides the operator with condition and safety information that will protect valuable equipment.

A control system diagram that shows the interaction between these various processing centers is given in Figure 1. This control distribution process is suggested from personal experiences gained from the application and development of several control systems applied to force-reflecting teleoperation. The result of implementation of a decentralized structure is a control system that can expand as improved sensory and intelligence technologies become available. The resulting common block approach also allows activity definition at an early stage so that multiple integrators can work on the development of control system software. The activity within a given control center varies depending of the present mode of operation. Local intelligence attempts to replace human intelligence during autonomous activities.

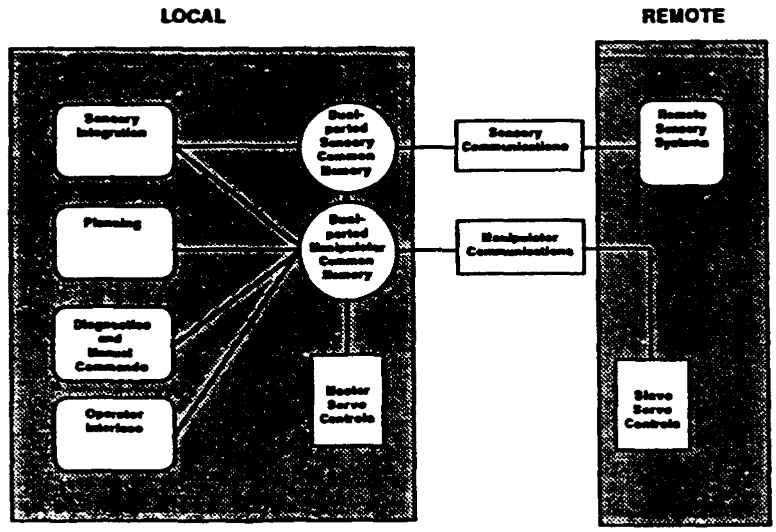


Figure 1. Conceptual layout of the principal control centers for telerobotic control.

3. Statement of the Problem

The functions described in the previous section can be accomplished in one or several processing systems. The essence of the problem is to determine the number of processors, the links between processors, the communications structure, and the upgrade development path that will provide the desired response, expandability, and computational performance required for a diverse and demanding group of control tasks to be developed over the next decade. Today's answers to these challenges are neither straightforward nor defendable as the technology will surely continue to advance. Certain approaches do have merit and should be supported in light of past experiences and anticipated advances.

The first architectural question that must be addressed is one of centralized versus distributed computation. Centralized processing refers to the use of a single, or small number of centrally located processors to accomplish all of the tasks described in Section 1. With distributed processing, a large number of less powerful processors perform multiple tasks simultaneously. There are arguments to be made for both sides. The use of centralized processors minimizes the communications and timing requirements and the synchronization that must occur if multiple processors must be utilized. Distributed, parallel processing systems provide enormous computational capabilities within a volumetrically small package. Hardware that uses both methods has been developed by the authors. Figure 2 shows the Model M2 control system that was developed at the Oak Ridge National Laboratory in 1982-84. It is a unique example of distributed digital control for force reflecting manipulator control. Utilizing over 30 microprocessors, this controller provides closed loop calculations at nearly 100 times per second. Such distribution allows online diagnostics, high speed loop closure, variable operation modes, and programmable operations to be accomplished at the servocontroller level. The system has performed very reliably for over 2 years of daily operation. The replication of an identical simple software package in each of the joints made the software development very efficient. The most complex portion of the control development was the sequencing of inter-processor communications. The greatest benefit of this form of control is the very small communications cable bundle between the master and the slave system. This system could be readily converted to wireless operation if desired. The greatest disadvantage to this implementation is the susceptability of the control components to the environment. This limitation can be addressed in future systems.

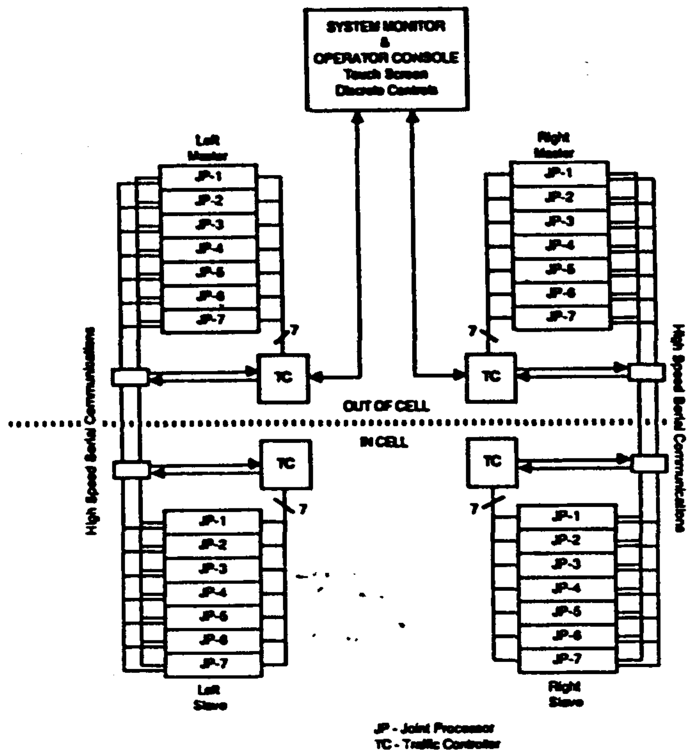


Figure 2. An example of decentralized force-reflecting manipulator control.

Figure 3 shows a general block diagram of a centralized control system. The control requirements of typical non-force-reflecting manipulators differ greatly from the M2 because the frequency response is much lower. As a result, a single host processor has the capability to sample, calculate, and control all of the functions at a much slower rate (~10 samples per second). If more diagnostic intelligence or force reflecting capabilities are to be added to this system, then the computational power must be increased. Additional processing power does not linearly improve calculational capabilities specifically because of the time required to communicate between computation centers. The REMOTEC RM-10A is an example of a non-force-reflecting centralized manipulator control system. The loop closure rate only effects the stiffness achievable in the servocontrol, but does not result in any noticable time delay between the master motion and the slave. The utilization of centralized control requires handling of a significant number of signal and power leads between the master and the slave system. The length at which this type of system will function is also limited due to lead resistance effects. The centralized control system is not amenable to wireless operation without the total redesign of the control electronics. This is not to say that the system has no merits. The centralized controller provides a cost effective, reliable means of performing limited manipulator operations.

The control systems selected for the Model M2 and the RM-10A manipulators were designed with the ultimate performance of the electromechanical system in mind. Force reflecting systems which require high throughputs of information have one level of control system calculational requirements. Non-force-reflecting systems with limited stiffness have a completely different set of control system needs. The design tradeoffs result from considerations of prototype cost, replication cost, performance needs, and reliability considerations. Both of these systems represent an implementation fit for its intended function.

To determine the duties of the control system, the next major concern that must be addressed is one of automation versus teleoperation. The course that NASA has laid out makes this determination very clear. It is a path that begins with teleoperation and evolves toward robotic operations. This means that the control system should be capable of both activities, teleoperation and robotics, and the architecture should be so devised as to allow expansion paths for future developments leading to sensory fusion and autonomous operations. The development of such a control system will result in the implementation of true telerobotic

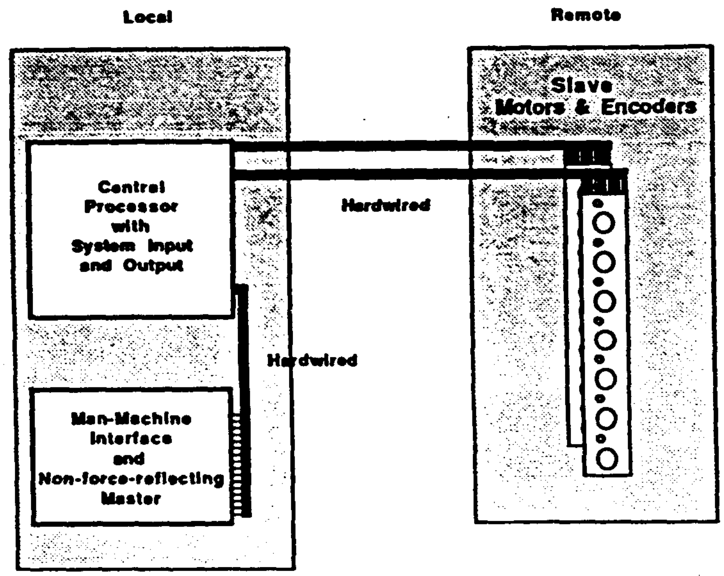


Figure 3. Example of a centralized controller for telerobotic control.

manipulation systems that work equally well under human or computer control. The elements of this type of control were shown in Figure 1. The majority of this paper will deal with those elements that are common to both approaches, the multimodal distributed servomechanism controller. By distributing the lowest function and highest throughput level of control, the distributed processing approach will assure expandability of the control system to future challenges and needs as they develop. The utilization of a common memory system allows definition of the present variable domain and can provide expansion to future variable domains.

4. Description of the Servomechanism Control System Architecture

The architecture of the servocontrollers in many ways determines the future expandability of the manipulator control system. While high level machine decisions are computationally intensive, the output data that results seldom has as high a bandwidth as the information passage between joints for master/slave operation. Sensory integration systems may have very high input data rates, but may only have limitedoutput needs. For example, a vision sensory/deciphering system has extremely high input bandwidths, but its output may be limited to geometric descriptions of the objects in the frame of view. Similarly, an operations planner may work on very large data bases, but its output results in high level commands that are not communications intensive (scan the past history of successful operations then determine the next step needed to accomplish a given task). The following is a description of the bottom-up approach focusing on the specific task of self-diagnosing servomechanism control capable of multiple modes of operation.

A prototype dual axis servomechanism controller has been developed with funding from the Department of Energy. The controller has the capability of acquiring data, receiving commands, and performing control activities for two servomotors. A detailed hardware description of the device is given in Section 5. The purpose of this development is to allow co-location of the controls with the motors to minimize cable handling problems, minimize the effects of environmental electrical noise, distribute the control complexity to its most fundamental level, and provide a system that is reliable and easily maintained. The resulting architecture is given in Figure 4. Each of the dual axis controllers shares a common serial communications bus and power bus. This yields a system that can be expanded significantly without experiencing cable handling problems that so often affect reliability. Using high speed serial communications, the serial bandwidth is sufficient to handle between 10 to 20 dual axis controllers. This architecture makes reconfigurable manipulation realizable for special applications targeted at space

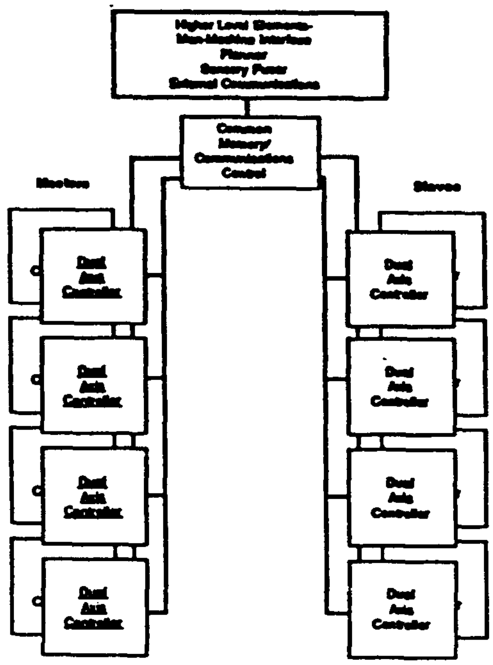


Figure 4. General architecture for manipulator control using dual axis controllers.

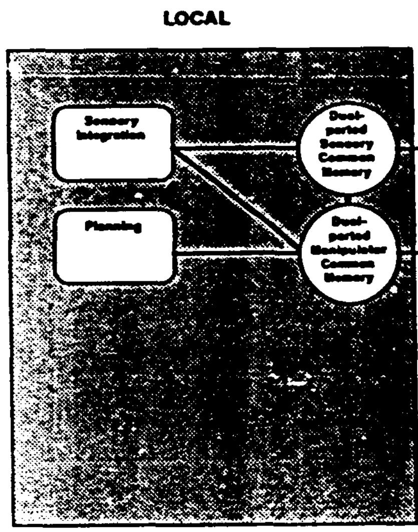
construction and ground maintenance. Major subsections of the dual axis controller are the processor, the input interface, the output interface, and the two amplifiers.

Each dual axis controller has a unique communications address and can respond independently to data requests made from a communications control processor. This processor sequences the data flow between dual axis controllers and the common memory area allowing dual ported access to the real time data collected and processed by other processing centers. The result is a high speed serial communications structure for the servomechanism control that is expandable to accomodate additional sensory and planning systems. The key to the success of this architecture is maintaining high bandwidth for the communications between dual axis controllers for teleoperation while allowing provisions for external computer control to sequence autonomous movements. The overhead associated with sequencing the different dual axis controllers must be kept to a minimum in order that the serial link between controllers hmaintain a high throughput rate.

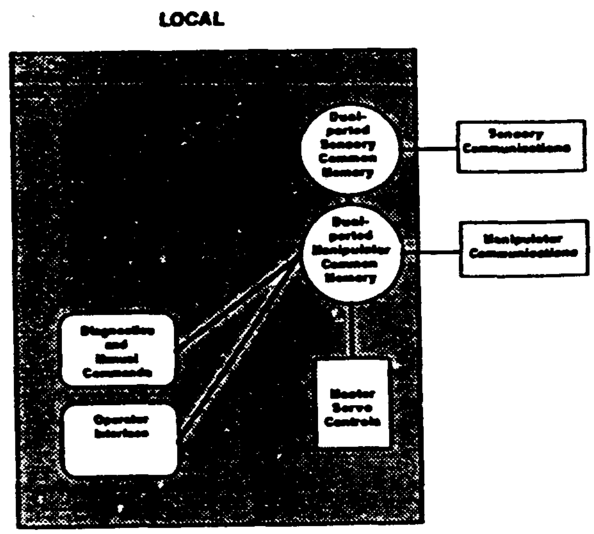
The human-machine interface represents the high level side of the manipulation control system. During teleoperation, the human performs the functions of sensory integrator, planner, and instigator of activities while the computer performs the role of diagnostician, monitoring the condition of the system hardware. The major activities are completely inverted during autonomous activities as the computer senses, plans, and implements motions while the human is placed in a position of supervision for the activity. This inversion of responsibilities is accompanied by an inversion of the internal computer communications requirements. During teleoperation, sensory processing systems and task planners are not needed to their full extent, but the communications path between the master and the slave needs to be left unimpaired to provide responsive force reflecting operation. Figure 5 shows the differences in the principal communications flow paths depending on the type of operation that is occurring.

5. Hardware Implementation of the Dual Axis Controller

A functional block diagram of the dual axis controller is shown in Figure 6. The major components include the processing system (Novix microprocessor), the input/output interface, the communications interface, and the amplifier system. These components work together to provide stable, multimodal control of a dual axis manipulator element. Operating modes that are either functional or under development



Primary active elements during autonomous tasks.



Primary active elements during teleoperated tasks.

Figure 5. Main active elements for robotic and teleoperated control.

include: position-position control with velocity feedforward, position control with integration, velocity control, intermediate path generation between communication intervals, torque control, joint initialization, and internal diagnostics. In essence, this controller accomplishes all aspects of basic servomechanism operation and diagnosis. The Novix computer forms the foundation of this system, and it will be described in detail.

The Novix computer represents a new generation of microprocessor hardware. This processor is designed in its internal architecture to execute a high level language (Forth) as its "assembly" language. The result is a processing system that is extremely efficient, independent, and compact. Since other popular processors (Motorola 68000 series, Intel 8086 series, etc.) operate in assembly languages from which higher level languages are constructed, the speed with which the Novix runs Forth programs approaches an order of magnitude increase over these other systems. This result occurs even though the present Novix configuration operates at a considerably slower clock cycle (4MHz versus >10MHz). This philosophy of developing a microprocessor engine that executes a language, rather than a machine level instruction set, is a concept that will certainly spread to future microprocessor architectures.

The Novix is available on cell libraries and can be integrated with other standard cell devices to allow microcontrollers for specific applications to be developed. The potential for intelligent sensors, miniature servocontrollers, parallel processing/transputing nodes, and powerful man-machine interface drivers is quickly becoming a reality. Some of the more impressive features of the Novix microprocessor include:

1) Executes 8 million operations per second of high level codes.
2) One-cycle local memory access.
3) One-cycle multiplication and division instructions.
4) One-cycle subroutine (word) nesting.
5) Executes most Forth primatives in a single machine cycle.

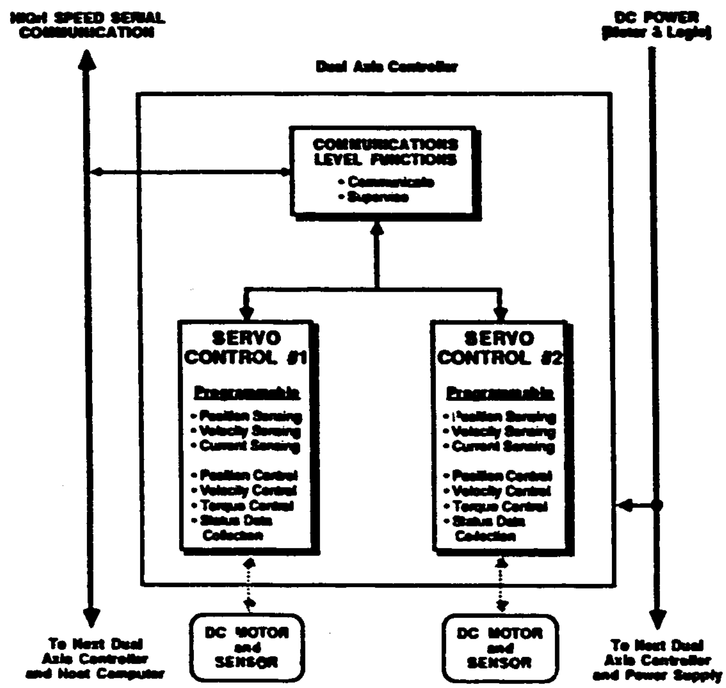


Figure 6. Dual axis controller functional diagram.

The dictionary structure of the Forth language allows the development of libraries of specific applicational words to be shared between programmers on similar systems. It also encourages top-down, bottom-up, or middle-out programming. This allows planning of the software functions to be accomplished in a number of ways allowing future software expansion capabilities. Figure 7 shows the hardware realization of this system in prototype form. A volumetric reduction of 50% will be accomplished to co-locate the motors and controllers within the joint module.

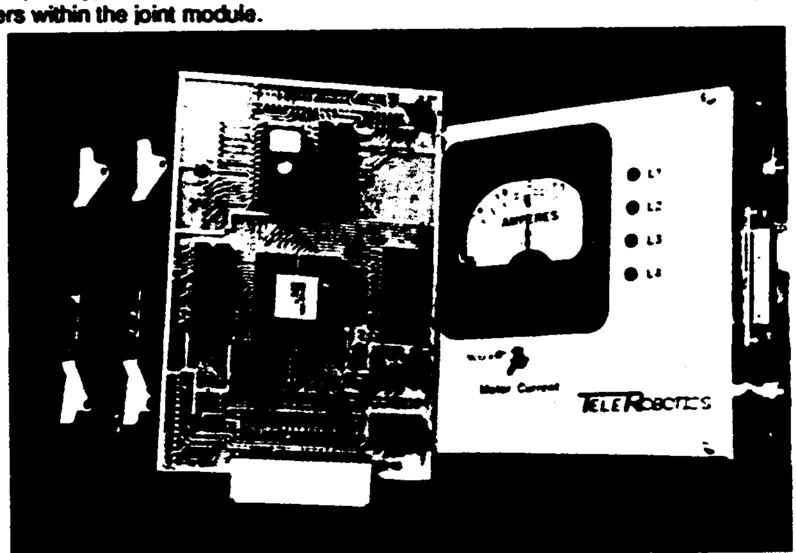


Figure 7. Dual axis controller prototype hardware.

6. Element for the Advanced TeleRobot (ATR)

The dual axis controller allows the co-location of controls and mechanisms into an entirely modular, self-contained unit. The advantages of this design and construction are numerous. First, each module can be replicated and utilized as a shoulder, elbow, or wrist joint. The shared power and communications keeps the cable handling at a minimum. The kinematic nature of the element allows reconfiguration of the joint motions to allow multiple kinematic construction to be accomplished (i.e., optimized kinematic arrangements for various task requirements). Remotely mated mechanical and electrical connections allow quick modification from one kinematic form to another. The basic mechanical element provides dual axis manipulation that can lift 30 pounds at 50 inches. Each element weighs less than 17 pounds. For ground based applications, a method of mechanical and/or electrical counterbalancing can be provided. The unit is backdrivable at approximately 20% of peak load. This allows compliant operation when the system is under external loads. The dual axis manipulator element is shown in Figure 8. The element is so versatile that it can be utilized as a camera pan/tilt device, a camera positioning device, and arm joint, or a torso positioner. More detail on both the mechanical and electrical implementations can be obtained from the reports "Analysis and Design Enhancements for the Advanced Servomanipulator" and "Using the NOVIX Computer for Control of Redundant Teleoperated and Robotic Manipulators" performed for the United States Department of Energy.

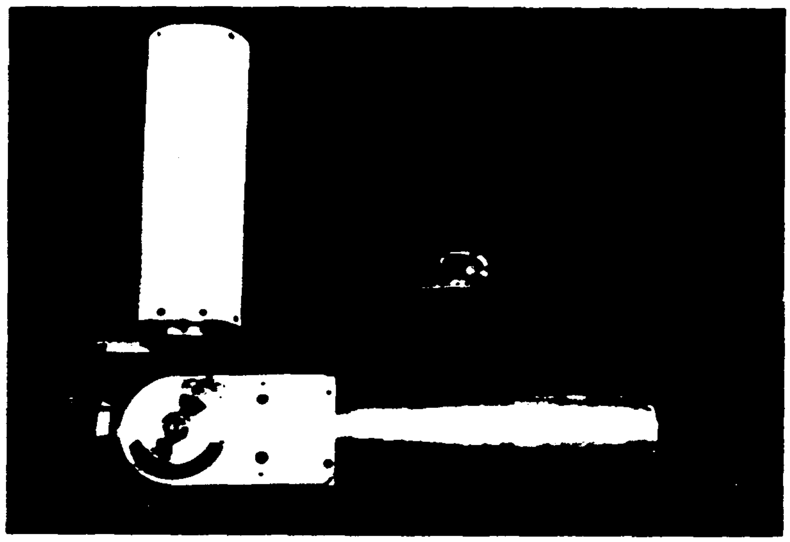


Figure 8. Dual axis manipulator element implementation.

7. Summary

A discussion of servomechanism control techniques for telerobotic systems has been presented and a brief review of two control approaches was given. The attributes of centralized and decentralized control were discussed from a perspective of applied experience. The reasoning behind the dual axis controller was developed and the general architecture reviewed. The actual implementation hardware for the dual axis controller has been accomplished and software for servocontrol has been generated. The dual axis manipulator element capable of redundant, replicated kinematic construction was introduced, and a functional prototype was described. These efforts represent a significant effort to move telerobotics ahead to meet future challenges for DOE, NASA, and the DOD. The approaches are novel and take a large step toward a reliable, inexpensive, and adaptable mechanical and electrical manipulation system. Incremental improvements were avoided, and completely new ways of accomplishing the objectives of remote manipulation were sought. The admirable performance of the prototype controls and mechanisms holds promise for future systems implementation.