

## CONSTRUCTION AND DEMONSTRATION OF A 9-STRING 6 DOF FORCE REFLECTING JOYSTICK FOR TELEROBOTICS

Randel Lindemann

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California 91109

Delbert Tesar

The University of Texas at Austin  
Austin, Texas 78705

### Abstract

Confrontation with difficult manipulation tasks in hostile environments such as space, has led to the development of means to transport the human's senses, skills and cognition to the remote site. We examined the use of advanced Telerobotics to achieve this goal. A novel and universal hand controller based on a fully parallel mechanical architecture is discussed. The design and implementation of this 6 DOF force reflecting joystick is shown in relationship to the general philosophy of achieving telepresence in a man-machine system.

### 1. Introduction

This paper describes the work undertaken at the University of Texas at Austin to construct and implement a force reflecting universal hand controller in a microprocessor driven testbed with an industrial robot as discussed in [1]. The Texas 9-string kinesthetic joystick has been interfaced to a robotic manipulator and a microprocessor to realize a prototype telerobotic system. The system is a generalization of the industrial bilateral master-slave teleoperator. The man-machine interface is universal and therefore capable of positioning and orienting any 6 DOF manipulator once the suitable transformation changes are made in the controlling software. The 9 string kinesthetic joystick represents the extension of force reflection to the original 9 string unilateral joystick developed by Tesar and Lipkin as discussed in [2]. The design of the joystick has been based on maximizing its capability to convey telepresence through a novel parallel architecture which is actuated in antagonism. The Texas telerobotics system represents an experimental test facility for research into the engineering and human factors issues of man-machine interface. In the table below the design goals of the project are given.

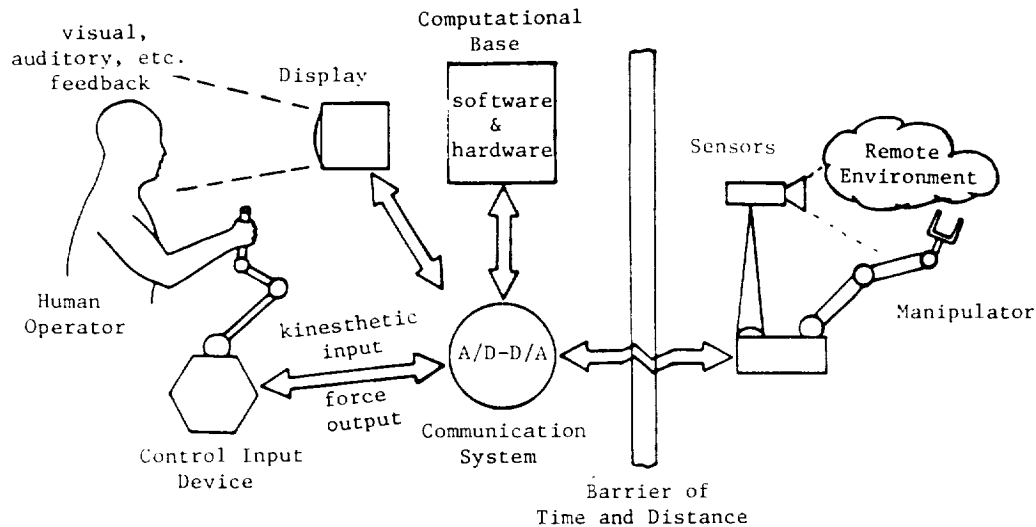
#### System Functional Attributes

- |                            |  |
|----------------------------|--|
| 1) decoupled interface:    | no geometric similarity required between master and slave  |
| 2) motion projection:      | projection of commanded motion                             |
| 3) variable control point: | electronic control point selection                         |
| 4) accommodation:          | manipulator motion is altered by the end-effector          |
| 5) coordinated control:    | operator directly controls end-effector motion             |
| 6) motion filtering:       | jitters and jerks in input motion removed                  |
| 7) positional scaling:     | variable positional gain between interface and manipulator |
| 8) indexing:               | controller repositioning                                   |
| 9) reorientation:          | compensation for operator perspective                      |

## 2. Man-machine interface

Because of man's need to have control or an effective presence to do manipulation in remote or hostile environments the teleoperator system (TOS) has been developed. These TOS have given man the ability to extend his strength and dexterity along with his intelligence into the remote site. Historically, the TOS consisted of two manipulator arms which were geometrically identical. One arm, called the master served as the control input device positioned by the operator. The other arm, called the slave, could if servoed sense and feedback its load state to the master arm.

The importance of TOS is in its capacity to extend to a human operator the remote control of the full 6 degrees-of-freedom (DOF) of rigid body motion through the positioning of one hand. In an advanced TOS the man is only one component along with the computational base, remote manipulator, display facility, sensory hardware, communication system, and the control input device. In figure 1 below, a schematic of such a generic system is shown with the arrows indicating the flow of communication signals.



*Figure 1: Advanced Generic Teleoperator System*

An important characteristic of a TOS is the degree to which the operator is made to feel he is at the remote site actually performing the manipulation task. This illusive design feature is termed 'telepresence'. Studies conducted on advanced TOS indicate the need for force feedback to the operator from the remote manipulator. Thus, the TOS must condense the vast quantity of data that is echoed back from the environment of the manipulator into a form favorable to human perception and interpretation. Simultaneously, the human's limited output must contain sufficient information for unambiguous interpretation by the computational base. The result is a very comprehensive control input device. To achieve the most effective relationship between the operator and the manipulator, the control input device or man-machine interface should be effectively transparent to the information flowing through it.

In order to function efficiently, the TOS used in general, unstructured tasks will require specific slave manipulator geometries which may vary greatly in size. The man-machine interface must be constructed with respect to its utility as a control input and kinesthetic feedback device. The intersection of these two demands dictates the need for a universal manual controller. The universal controller is one which is fully software driven and requires a computational base or machine intelligence to drive two geometrically dissimilar manipulator arms. The inclusion of a

machine intelligence into the TOS, frees the man-machine interface designer from the restrictions of kinematic replication and limited control in the development of a generalized master-slave TOS.

As indicated earlier, the state-of-the-art in TOS are replica (geometrically identical) master/slave systems, essentially a 30 year old technology that will not be adequate in difficult task environments such as orbital and interplanetary space. These systems lack transparency in the bilateral flow of communication that causes the operator to be between 2 and 20 times as slow as his functioning without a TOS, and generally precludes altogether complex tasks.

Our belief is that the most effective TOS will incorporate a universal man-machine interface optimized in its design to the relevant human factors involved in order to achieve telepresence. As a result the man-machine interface will have a geometry distinct and decoupled from that of the manipulator being controlled. The interface will then require a computer to augment the human intelligence as a computational base performing the needed geometric transformations between the man-machine interface and the manipulator. The form of this idealized controller is a universal bilateral position controller.

Advances in the last 25 years have also led to the development of programmable and autonomous manipulator arms called robots. A recent result has been their combination with TOS into a hybrid form of system called 'telerobotics'. The resulting system can be defined as a robotic system which in addition to its usual autonomous modes of operation can take control information directly from a human operator through a man-machine interface thus becoming teleoperated; or from a higher, supervisory level of executive control, thereby acting in a semi-autonomous manner. By making the universal master controller bilateral, the resulting system becomes conceptually two dissimilar cooperating robots, software coupled and running in real time.

### **3. Design and Analysis**

In the past, problems with man-machine interfaces have included their inertia, backlash in their drive trains, friction, and limited or non-ergonomic motion capability. Transparency in the flow of communication signals requires that the inertial dynamics and friction effects of the man-machine interface be well below the intended feedback level in order to avoid operator confusion between signal and noise. In this project an isotropic controller has been sought with a constant (but programmable) joystick-to-end-effector position mapping and end-effector-to-joystick load state mapping.

Usually in a TOS or telerobotic system the hand controller is designed around the robot or remote manipulator arm which is designed around the tasks it is meant to perform. In contrast, our goal has been to design a universal man-machine interface around the human operator and use the necessary geometric software transformations in a computer. The forerunner of this project is the work of Lipkin (1983) in the design and construction of a unilateral 9-string joystick [3]. This work had then been followed by the initial configuration study for a 9-string bilateral joystick finished in 1986 by Agronin [4].

Therefore, we designed the joystick to minimize the interface dynamics and maximize the force feedback capability. In order to reduce the inertia associated with each of the air cylinders, an optimization has been performed and the point near the air cylinders closest to its moving centroid has been chosen as the pivot point in order to minimize the inertia. The air cylinder is connected to a universal joint by brackets. An additional benefit to this choice is that the air cylinder is supported near its center of gravity and most of the weight of the air cylinders is off loaded.

In order to maximize the force feedback a geometric optimization of the geometry of the 9-string joystick has been performed. The optimization has been used to design for the largest fixed minimum of maximum force feedback for use in the open loop control of the feedback signal. In

order to assure an isotropic nature to the force feedback, the smallest maximum force that can be generated anywhere in the joystick workspace in any direction is the limiting factor. In order to maximize that quantity an analysis has been completed which relates the minimum force maximums to the geometry of the base triangles (where the cables emanate from the supporting structure of the joystick frame), the distance from the base triangle to the center point of the joystick workspace, and the air cylinder constant force.

The analysis approach (detailed in [1]) finds the algebraic rule that expresses the minimum of maximum force in a plane and then rotates the plane about the workspace center point and the line of action of air cylinder constant force. The calculus of minimization in one variable has then been used to find the minimum of force maximums. The technique has then been developed into a computer program which uses a global search technique to scan the joystick workspace. The program is interactive and the user inputted design factors in an adaptive fashion. The force feedback has been found to degrade as the volume of workspace increases. The final design chose an equal angle of 34.5 degrees between the strings and air cylinder shafts at the workspace center point, a pivotal offset of 0.0 inches, and an equilateral base triangle dimension of 20.83 inches.

As indicated earlier, the inertial dynamics of a kinesthetic controller is an important description of its quality of transparency or fidelity (signal-to-noise ratio). Therefore, a method of dynamic simulation has been performed based on the method of Tesar and Freeman [5]. The method uses dynamic equations based on influence coefficients which separate the purely position dependent functions from those which are time dependent (velocity, acceleration, etc.). An interactive program has been written and run simulating the Texas 9-string joystick undergoing a variety of path motions under representative velocities and accelerations.

The results of the simulation can only be summarized here (see [1]); but showed the inertial forces to remain at below 3% of the intended force feedback level even when the velocities and accelerations of the handgrip were at their peak representative values. The relatively small level of inertial force disturbance is to be expected as this along with high stiffness are representative properties of parallel mechanisms.

The choice of joystick working volume or that workspace the T-shaped handgrip can be moved within has been based on information found in the literature on other manual controllers which showed no debilitation using workspaces in the vicinity of a 12 inch cube [2]. Since an initial decision to use 18 inch stroke air cylinders as the compressive actuators had been made, the resulting approximate workspace of an 18 inch sphere has been deemed acceptable.

### JOYSTICK DESIGN OBJECTIVES

joystick workspace	18 inch diameter sphere
dexterous workspace	10 inch diameter sphere
incremental translation	.13 inch
orientational range	180 degrees (3 axis)
incremental orientation	1.1 degrees
force feedback range	0 to 10 lbf
torque feedback range	0 to 24 inch-pound

In figure 2 below, we see the annotated schematic of the Texas 9-string kinesthetic joystick. The two upper (vertical) planes of the joystick frame are constructed of clear acrylic in order to not obscure the operators' vision as the robot work area is in front of the joystick and slightly to the right.

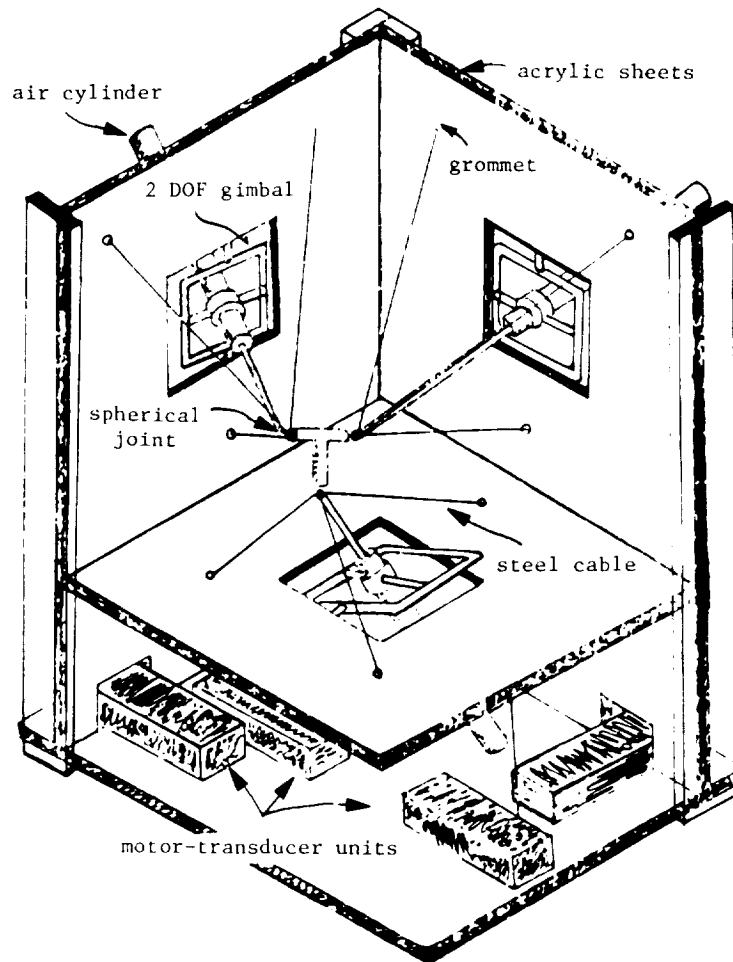


Figure 2: Texas 9-String Kinesthetic Joystick

#### 4. Implementation

The handgrip position and orientation of the joystick is calculated in the dedicated microprocessor from the lengths of the 9 steel strings. The string lengths are measured by custom made rotary potentiometers. The microprocessor then maps the handgrip position and orientation to the end-effector of the robot. This mapping exists in software and can be scaled by the operator. Simultaneously, the robot end-effector load state is measured and mapped to the handgrip of the 9 string joystick.

A general transformation is used to map from the 6-dimensional force space of the robot end-effector to the 9-dimensional force space of the joystick. The 9-dimensional force space of the joystick is represented by the 9 independent servoed cable tensions, which can only act in tension, thus requiring the 3 constant forces of the compressive actuators in order to generate an arbitrary force at each connection of the 'T' shaped hand-grip. Force Feedback is accomplished by holding the three air-cylinders at constant pressure and then controlling the tensions in the strings via current controlled servo-motors. As the problem of determining the cable tensions is underconstrained, an optimization has been performed to minimize the sum of the squares of the cable tensions. In mathematical form this is known as the pseudo-inverse of a non-square matrix.

The dedicated microprocessor is a DEC Microvax II. The Microvax II computer represents the computational base for the application of the transformations, filtering, communications, and

control activities present in this system. With a sufficiently fast protocol for communications to and from the robot controller, the Microvax II would represent real-time computing power for this level of task.

Each DC motor-transducer unit consists of a high-resolution .1% linearity rotary potentiometer attached to a spool wound with a steel cable. As the cable or 'string' is unwound from the spool, its length is proportional to the potentiometer resistance. Analog voltage measurement across the potentiometer can then be calibrated to the string length. The voltage readings from the transducers are continuous values which are converted via the DEC ADV11-C analog-to-digital converter board to digital information for the computer. Each transducer is driven by a brushless DC servo-motor to control the tension in the string. The Harowe motors are DC permanent magnet and brushless servo-motors with a stall torque rating of 35 pound-in.

The force feedback control signals from the Microvax are converted by the DEC AAV11-C digital-to-analog converter to the continuous voltage signals needed for the Benton SC-10 servo controllers. The servo-controllers operate in a current regulating manner to drive the DC motors. The use of a current control scheme over that of a voltage controlled one is critical to the performance of the 9 string joystick. The motor torque is proportional to the applied current. If the motors are powered in a voltage controlled mode then a back EMF forms which reduces the motor armature current. This results in the reduction of motor torque due to the circuit dynamics. This effect is equivalent to a mechanical damping. The magnitude of system dynamics is large enough to interfere with the operator's sensing of force feedback. In figure 3 below, the complete U.T. telerobotic testbed is shown.

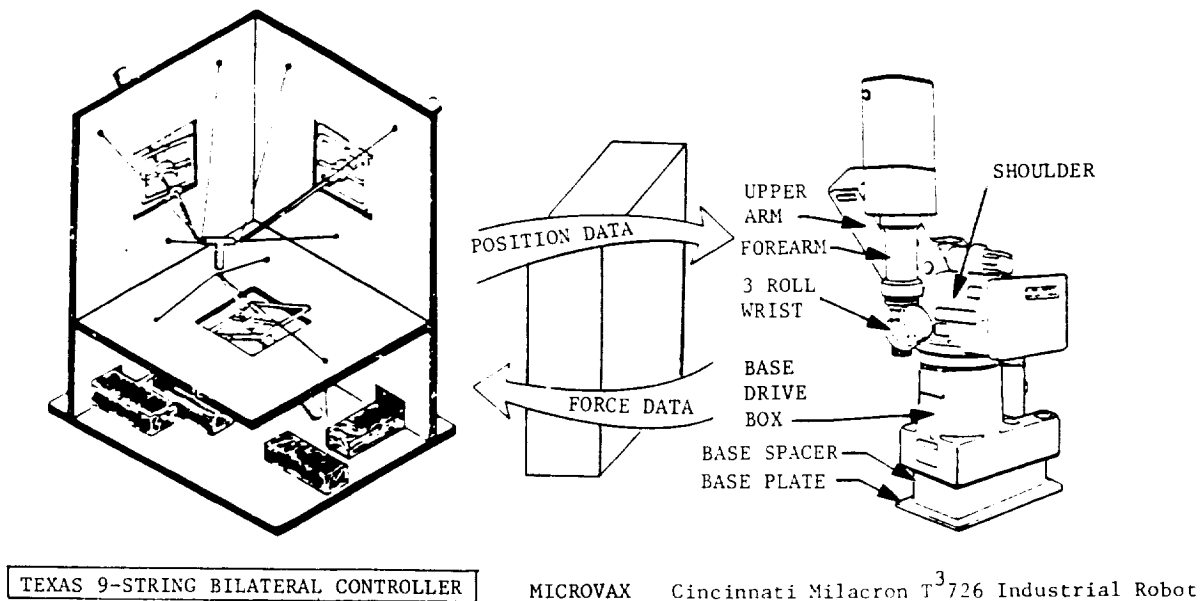


Figure 3: U.T. Telerobotic Test Facility

The three air cylinders represent the prismatic joints in the legs of the Stewart-platform parallel mechanism. The compressive actuators are Benton B-120 single ended, 18 inch stroke air cylinders. Each air cylinder is supported by an adjustable bracket to the center of a 2 DOF gimbal or hook's joint. The end of each air cylinder shaft is connected to a 3 DOF spherical joint,

composed of a steel universal joint with a ball bearing at each end. One spherical joint is connected to the end of each one of the three arms of the 'T' shaped aluminum handgrip. At the connection of each spherical joint to an air cylinder shaft, three steel cables are attached. The intersection of the three strings with the air cylinder axis represents the point where the force at that arm of the handgrip is generated.

Consequently, an arbitrary force vector (magnitude bounded) can be applied to each arm of the 'T' shaped handgrip. Each force vector is limited by the applied maximum string tension. The three triad force vectors sum to produce the desired force and torque state at the center of the joystick grip.

Software has been provided by the manufacturer to interface the Microvax II to the controller of the Cincinnati-Milacron T<sub>3</sub>-726. The Cincinnati-Milacron Inc. (CMI) host software is responsible for a time lag in the communications rate. The CMI software uses a non-real time protocol system known as DDCMP.

The load state at the robot end-effector is sensed by a commercially available force/torque sensor. The sensor is a Lord corporation model 15/50 load cell. The model 15/50 is mounted to the wrist of the robot, and a connection is provided to affix a Telerobotics International EP 100/30 robot gripper. The force sensor and the robot gripper are both driven by software implemented on the Microvax II. The robot end-effector is utilized by the telerobotic system operator via an on-off control button box. The button box is small and designed to be held in one hand by the operator to control the robot end-effector, while the other hand is in bilateral control with the robot arm.

The fully integrated telerobotic system is represented in figure 4 by a signal flow chart. After the system undergoes the startup procedures the T<sub>3</sub>-726 is placed in a remote mode in which the Microvax computer becomes a peripheral to the robot's controller. The operator then controls the system at two levels. In the first level, he must enter instructions into a menu-driven interactive routine on the computer terminal. At this stage, the operator can determine which control mode is desired. The different options available include; position-only control, resolved motion rate control, and kinesthetic control. In addition, the operator has the ability via the menu-driven terminal display to modify the spatial correspondence between the robot and the 9-string joystick. The operator can rereference the fixed joystick workspace to a new region of the robots workspace, he can scale the position and force mappings between the robot and the joystick either up or down from unity, and he can perform a smoothing operation on the position data to remove jitter from the robot's motion.

In the second level, the operator has placed the system software into control mode. The telerobotic system is then active. The operator by moving the handgrip within the limitations of the joystick workspace performs either a proportional move or sets a proportional velocity into effect for the robot end-effector. If the kinesthetic control loop is active, when the wrist of the robot is loaded by forces and torques, a scaled equivalent force and torque state at the operator's hand is generated.

Testing of the DC motors has shown that a stall force greater than 12 pounds for several minutes yields high motor temperatures and declining performance. Therefore, the system is operated in the kinesthetic mode with a maximum string force of 12 pounds. From our design optimization procedure we calculated the pneumatic system set point and the maximum available force reflection for each triad of the joystick. The air cylinder constant force has then been set to  $|F|=14.83$  pounds or 12.06 psig. The result is a maximum force feedback signal of 3.25 pounds at each arm of the 'T' shaped handgrip without affecting the isotropic nature of the force reflection. This corresponds to a range of force/torque feedback for the handgrip from a pure maximum force capability of 9.75 pounds in any direction, to a pure maximum torque capability of 43 in-pounds about any axis.

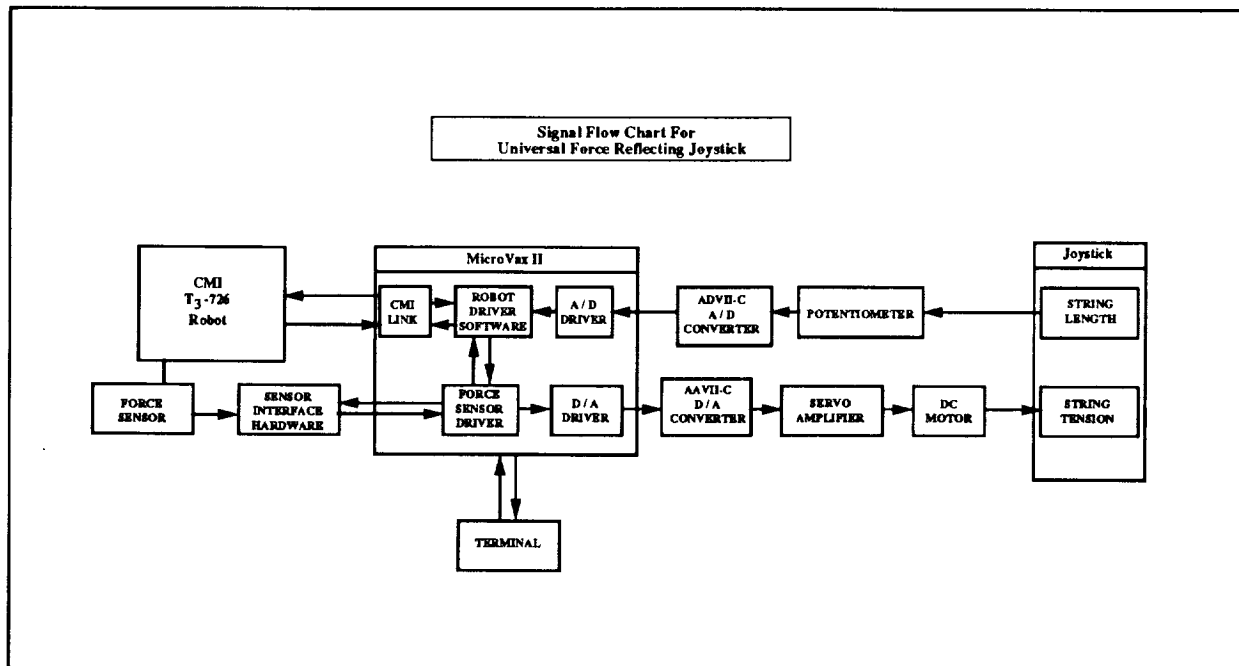


Figure 4: Testbed System Communications

## 5. Conclusions

Current methods of control use limited, corrupted, or inappropriately coded information to the human operator as well as hardware and software of insufficient power, generality, and dexterity to exploit the full capacity of telepresence.

The uniqueness of the 9 string joystick's geometry, the portability of its software, and the kinesthetic attractiveness of its operation make this man-machine interface a break with past engineering work in hand controllers and an excellent analysis tool for R&D.

The Texas telerobotics testbed after completion has been evaluated and found to be functional, yet showing significant detractions. Indicating the importance and difficulty of achieving real-time telepresence in telemanipulation. The most crucial detraction to performance is the existence of a high level of coulomb friction in the joystick mechanism. The effect is concentrated in the sliding joint of the air cylinders. The implementation of a pneumatic system resulted in a masked force feedback, which blocks the joystick's transparency to bilateral communication flow. The friction force also had the effect of making small precise motions difficult.

The high level of friction force in the pneumatic system also had the effect of obscuring the importance of friction from the motor-transducer units, and the inertial forces incurred in moving the joystick. A number of alternatives to a passive pneumatic system were considered such as motorized capstan, linear induction motor, and a linear mechanism employing a constant force spring. Another significant limitation to system performance is the slow update rate, or system cycle time. The protocol that allows information from the T<sub>3</sub>-726 controller to be sent to, or received from the MicroVax II computer is not sufficiently fast to fulfill our design goal of achieving a 30 Hz run-time bilateral mapping.



The resulting update rate of 9-10 Hz represents a significant reduction in performance. The operator becomes cognitive of this time delay during precise positioning. Also, the time delay produces increasingly jerky motion in the manipulator as the distance between subsequent sampling points grows.

In its present form the Texas 9-string kinesthetic joystick represents a proof-of-concept for a universal, parallel 6 DOF force reflecting manual controller for telerobotics. It does not yet achieve the demanding characteristics of transparency to information flow, and the system does not yet achieve the goal of telepresence. Currently, it is not expected to pursue improvement in the Texas 9-string joystick; but rather to use it for research into the issues necessary to design the next generation of man-machine interfaces. Current thinking for next generation interfaces include advanced hand-controllers based on redundant and hybrid (parallel and serial mechanical architecture) design as discussed by Sklar in [6].

Primarily, the research use for the Texas 9-string joystick is in such areas as human factors engineering. Results from that work would then push the design of man-machine interfaces based on a quantified understanding of issues such as joystick inertia, friction, cycle time, work volume, etc.

## References

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