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SUPERVISORY CONTROL OF REMOTE MANIPULATION: A PRELIMINARY EVALUATION

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ABSTRACT

Supervisory control, where control is traded between man and computer, may offer benefits in the control of a remote manipulator. A system for the study of supervisory control is described, and some preliminary results presented.

I. INTRODUCTION

Man's technological rise has been accompanied by an increasing need for him to work in hostile environments. Nuclear waste disposal sites, radioactive laboratories, the depths of the ocean, the vacuum of outer space, and underground mines are examples of such environments. Teleoperator systems project man's manipulatory capabilities into the remote environment, allowing his functional presence without his physical presence.

The need for teleoperators implies operating conditions which exclude or impair visual or other human sensory contact between the operator and the manipulator. The barrier imposed by the hazardous environment carries with it limits on both sensor and control communication.

It is possible for a man and computer to cooperate in the control of a remote manipulator, and achieve a standard of performance beyond that possible by either alone. This mode of control has been termed supervisory control [1].

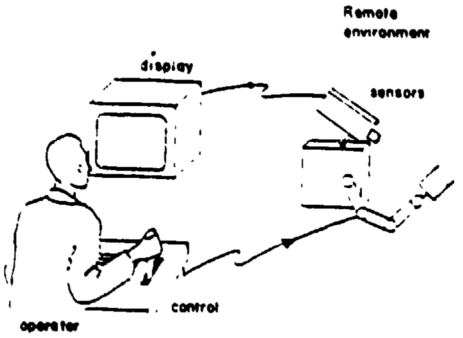
The first manipulators were master-slaves used for radioactive materials handling. They provided bilateral force feedback, and the operator viewed the site directly a few feet away. In this environment the operator was capable of precise positioning and fine control of applied forces. However, as the linkage between human operator and manipulator was made electrical, and the distance increased, the impairment of sensory feedback made control more difficult.

The first sensory degradation that was investigated was a transmission time-delay between the operator's command and the manipulator's response. A time-delay can arise from extreme separation (outer space manipulation), or sensor/display limitations such as limited video frame rate.

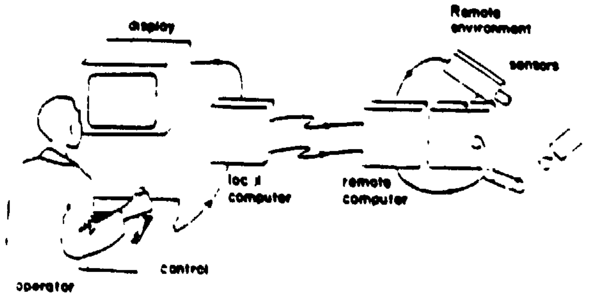
Ferrell [2], Black [3], Hill and Sword [4], and Starr [5], experimentally verified the negative effects of time-delay on manipulation. Simple tasks became frustrating and laborious, and manipulation requiring high accuracy was virtually impossible.

Supervisory control may allow manipulation to be performed effectively even when a time-delay is present. The philosophy of supervisory control is that the human operator plans strategy, monitors performance, and intervenes when necessary, while the computer accomplishes portions of the task as instructed by the human. Supervisory control allocates control responsibility between man and computer such that the inherent attributes of each are used to best advantage.

Figure 1 shows diagrams of manual control and supervisory control of a remote manipulator system. Under manual control the operator's commands are sent directly to the manipulator, and feedback from its sensors is displayed directly to him. Under supervisory control the operator's commands are transmitted to a remote computer, which then commands the manipulator. The remote computer also processes the sensory information from the manipulator and relays it to the operator. Since the remote computer is "on site" it is



MANUAL CONTROL



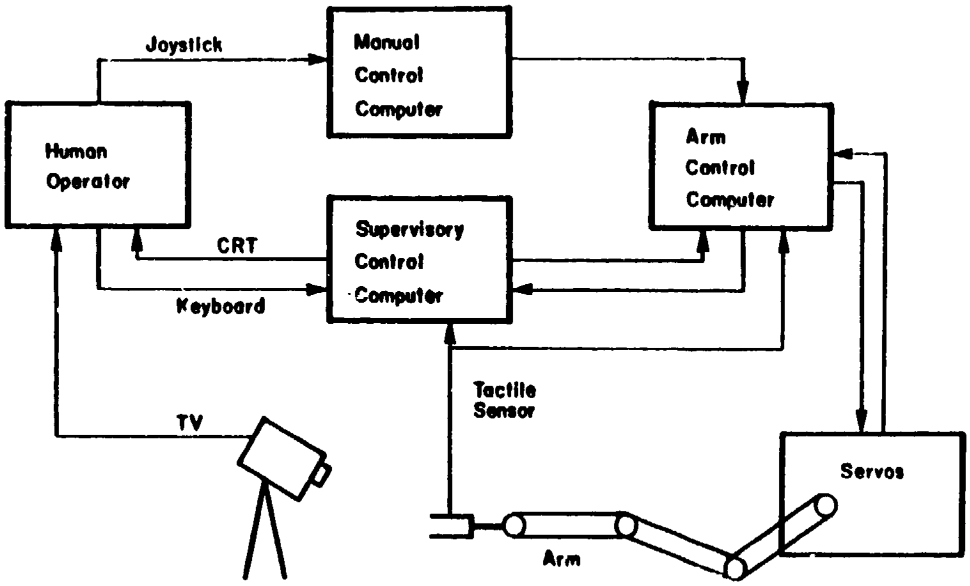
SUPERVISORY CONTROL

Figure 1

not subject to the same feedback degradation as the human operator. The portion of the system comprised by the manipulator and remote computer can accomplish portions of the task on its own. The human functions principally as coordinator and supervisor, but may still control the manipulator directly if necessary.

II. SYSTEM OVERVIEW

Figure 2 shows a block diagram of the system. There are three separate digital computers, each with its own responsibilities. The Manual Control Computer (MCC) processes manual control signals originating from the human operator. The Arm Control Computer (ACC) performs arm trajectory calculation, monitors the jaw-mounted tactile sensors, and drives the arm through desired positions. The Supervisory Control Computer (SCC) monitors the sensors, sends commands to the ACC, and performs quantitative analysis of arm positions and sensor data.



BLOCK DIAGRAM OF SUPERVISORY CONTROL SYSTEM

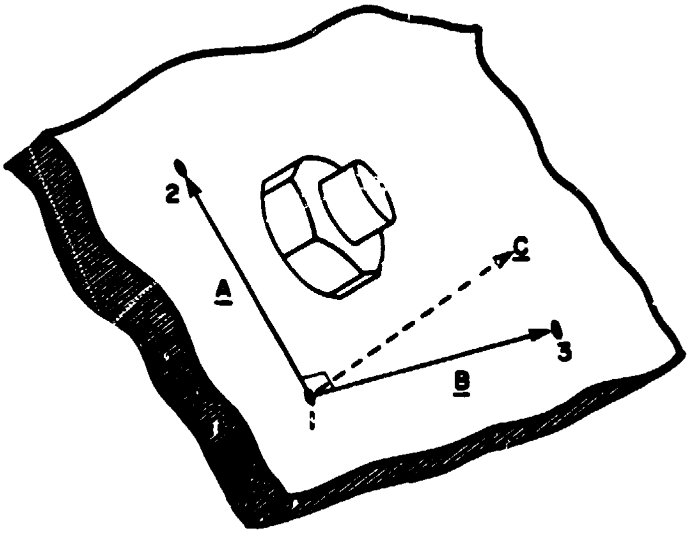
Figure 2

The SCC and ACC are coupled by a 9600 band serial communications link. The ACC executes the VAL language while the SCC uses the RT-11 operating system, with programs written in FORTRAN or assembler language.

Example of System Operation. Although the individual elements in the system will be described later, the following alignment routine (used in the experiments) is an example of how they work together.

Consider the operation of removing a nut from a stud, when the plane on which the stud is fastened is arbitrarily oriented and the manipulator hand is "far away" from the nut. Before a pre-programmed nut-removal routine can be executed, the nut must be approached, and the hand must be "lined up" with the axis of the nut, i.e., normal to the plate. The sequence of operations is as follows (see Figure 3):

1. The human operator brings the hand to the vicinity of the nut, manually orients the hand to be roughly normal to the plate, then instructs the SCC to execute the "ALIGN" routine. The SCC commands the ACC to execute its stored alignment routine. The ACC advances the hand in the direction it is pointing until it touches the plate at location 1.



1. MAN MOVES ARM TO TOUCH AT "1"
2. COMPUTER MOVES ARM TO TOUCH AT "2" AND "3"
3. VECTOR $\underline{C} = \underline{A} \times \underline{B}$ COMPUTED
4. COMPUTER ORIENTS HAND ALONG $\underline{C}$
5. CONTROL RETURNED TO MAN

ALIGNING HAND WITH BOLT AXIS

Figure 3

2. The ACC detects the touch, stores the position where the touch occurred, and moves the hand to touch the plate at locations 2 and 3, storing these locations.

3. The three locations define vectors A and B, from which vector C is computed by the ACC.

4. The ACC drives the hand to point along C. The hand is now aligned with the nut axis.

5. The SCC notifies the human operator that the hand is aligned, and displays the options for continuation, which may include resumption of manual control, or invocation of another computer routine.

The remainder of the paper will be devoted to describing the elements of the system and discussing a preliminary experiment and results.

III. MANIPULATOR

The manipulator is a PUMA 600 manufactured by Unimation, Inc. The arm, shown in Figure 4, has six revolute joints, each powered by a DC servomotor. The arm has a position repeatibility of 0.1 mm (0.004 in.). It can apply a static force of 58.0 N (13.0 lb). Its length is approximately one meter.

Each arm joint is under the local control of an R6503 8-bit microprocessor, which receives commands from the Arm Control Computer (ACC), a DEC LSI-11. Each 6503 has its own PROM, RAM, and I/O logic, and servos its joint via a D/A converter and shaft encoder.

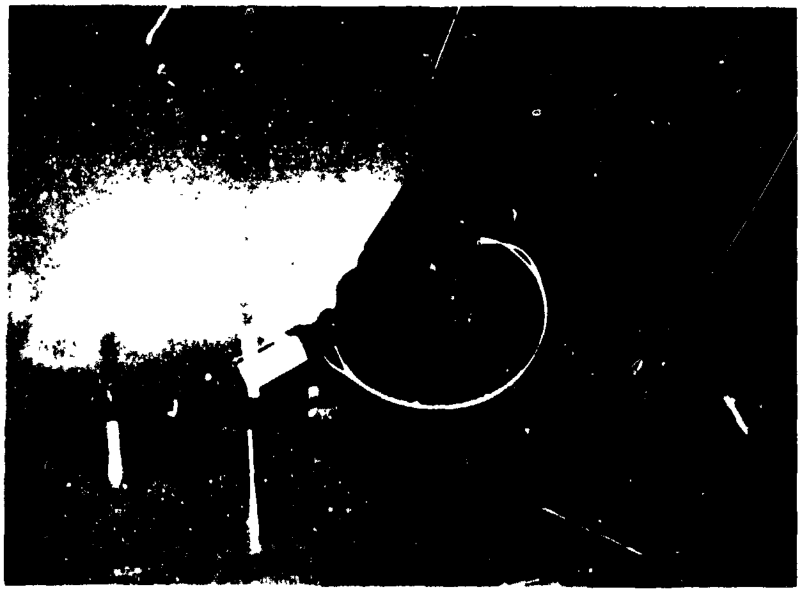
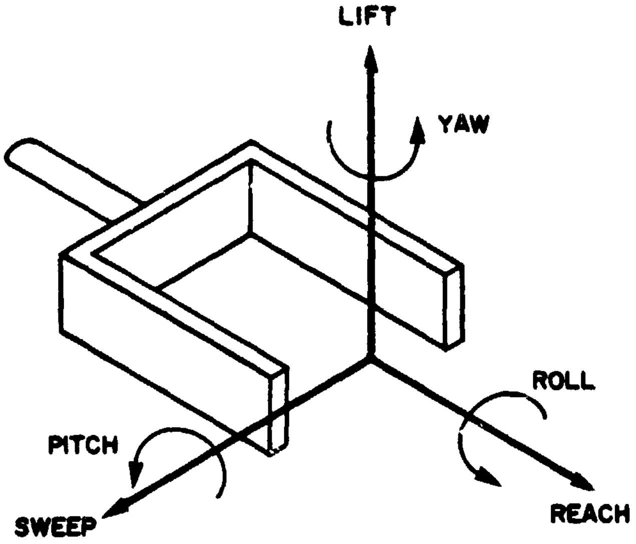


Figure 4

IV. MANUAL CONTROL SYSTEM

Resolved motion rate control (RMRC) is the manual control mode. With RMRC, the operator uses a six degree-of-freedom isometric joystick to specify velocity components of the hand along axes of a hand-mounted cartesian coordinate system. The hand-mounted coordinate system is shown in Figure 5.

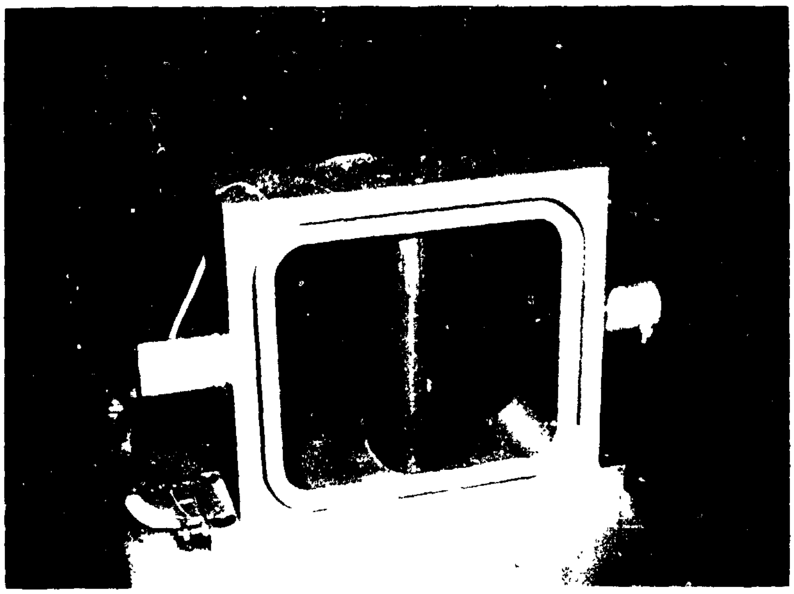
The six degree-of-freedom isometric joystick, shown in Figure 6, produces six output signals proportional to the six applied forces and torques. The magnitude of a force/torque component determines the value of corresponding translational/rotational velocity component. Thus, if the operator pushes forward on the joystick, the hand moves forward (in the direction it is pointing); if he pushes down, it moves down, etc. The coordinate transformations necessary to drive the hand along the cartesian directions are performed by the Arm Control Computer (ACC), which computes arm positions each 28 msec.



HAND – MOUNTED COORDINATE SYSTEM

Figure 5

The six velocity commands from the joystick do not go directly to the ACC, but are first processed by the Motorola 6800-based Manual Control Computer (MCC). The MCC does the following:



6 DOF JOYSTICK

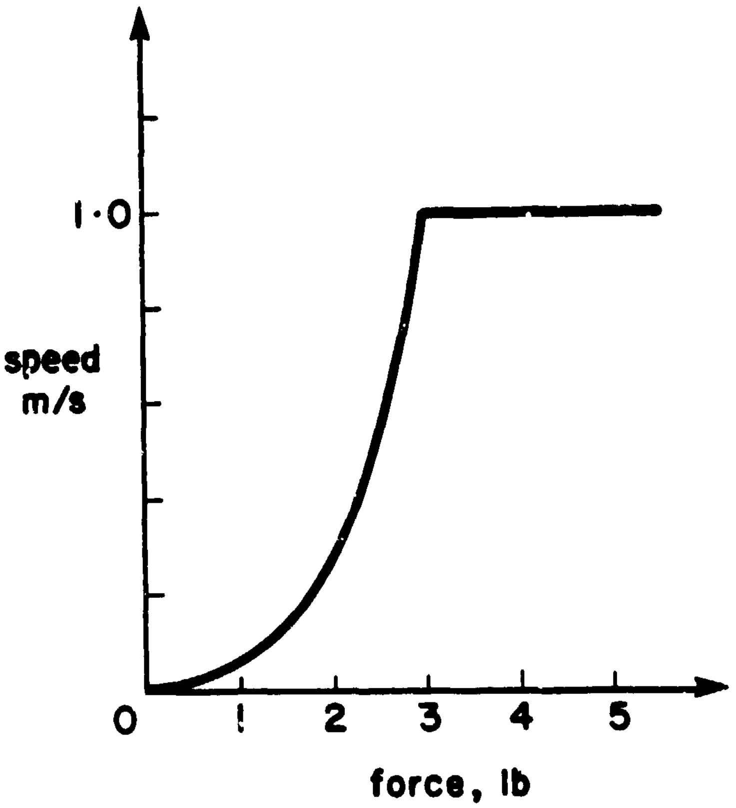
Figure 6

1. Provides nonlinear joystick force/hand velocity relationship. To get good manual control at low hand velocities, and still be able to command high speed without excessive joystick force, a cubic force/velocity relationship is implemented. Done in real time with an AMD 9511 floating point processor at a sampling rate of 50 per second, the cubic relation is shown in Figure 7. We obtain low sensitivity for low joystick force, and high sensitivity for high force. Thus, the arm can be easily driven at its minimum speed, and may still be driven at maximum speed without requiring excessively large or small joystick force.

2. Implement a time-delay. To realistically evaluate the supervisory control manipulation system, a communication barrier must be imposed between human operator and arm. The most studied, and easiest to systematically vary, is a pure time-delay. A time-delay between joystick and arm is produced by the MCC, and may be varied from zero to 10 sec, with 0.02 sec resolution.

3. Joystick deadbands. Since velocity control is an integrating process, any hysteretic joystick signal after the operator releases the joystick will cause undesired arm motion. Software deadbands in the MCC prevent this.

4. Computer control takeover. When the operator wants to switch to computer control mode, he depresses a button. On receipt of this signal, the MCC immediately switches the ACC to computer mode (from manual mode),



HAND VELOCITY VERSUS JOYSTICK FORCE

Figure 7

then after 0.05 sec the MCC issues a command to the SCC. This causes the SCC to either prompt the operator for a command, or begin a preprogrammed activity in conjunction with the ACC. The 0.05 sec wait is necessary to allow for mode-switching time in the ACC.

Note that even though this control mode is denoted manual control, it is actually a form of computer assistance where the MCC and ACC are in series with the human operator.

V. SENSOR

A jaw-mounted tactile sensor is used as the arm-based environmental sensing element. The sensor consists of a number of arrays of rectangular plates, each of which is sensitive to force. The sensor/jaw appears in Figure 8. The sensor arrays are connected to the SCC and the ACC via a multiplexer, so that when a contact is sensed, both the face of the jaw and the particular plate responsible for the contact are known.

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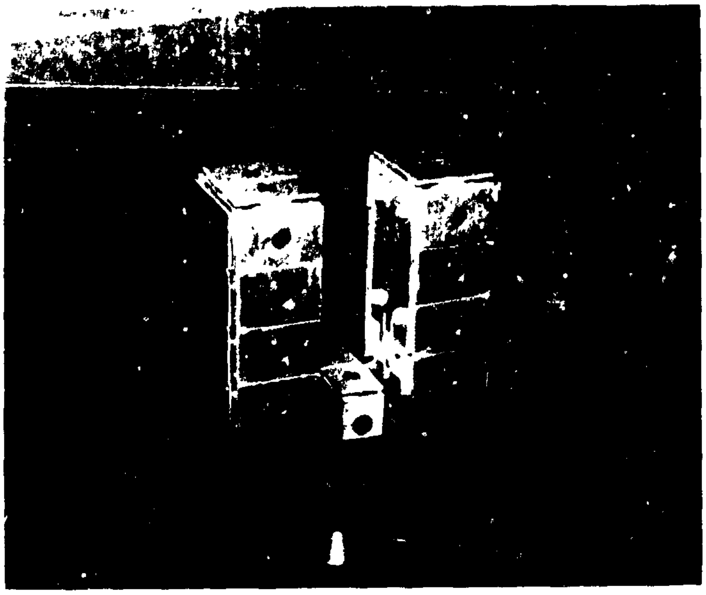

TACTILE SENSOR JAWS

Figure 8

VI. COMPUTER CONTROL SYSTEM

The computer control system consists of two separate computers, the ACC (Arm Control Computer) and the SCC (Supervisory Control Computer). Both are DEC LSI-11 microcomputers. The ACC and the SCC work together in controlling the manipulator. Some functions performed by each machine are:

Supervisory Control Computer (SCC):

1. Can cause execution of a given ACC arm control program.
2. Read and store arm positions, numerically analyze them, take action.
3. Scan sensor, take appropriate action on contact.
4. Display prompting or status information to human operator.

Arm Control Computer (ACC):

1. Calculate trajectories, drive arm at desired speed.
2. Modify stored arm positions to be relative to new reference.
3. Read sensor, use data to govern program branching, cause jump to subroutine.
4. Execute stored routine upon request from SCC.

While some functions are common to both, the SCC controls the arm at a higher level, selecting ACC programs to executed, analyzing positions, communicating with the operator. The ACC does the lower-level arm control, calculating trajectories and issuing joint commands.

One extremely useful capability of the ACC is that of relative positions. Preprogrammed routines can be "taught" in the laboratory, with all positions being defined relative to some reference position ("position" implies here a six-dimensional quantity including position and orientation), which is also defined at this time. When the preprogrammed routine is invoked in the field, the reference location will in general be different than that in the laboratory. The first instruction in the ACC routine can be a redefinition of the reference position to that which exists at that time. Upon execution of the routine, the ACC transforms all relative positions to be relative to the newly defined reference position. This yield the same relative hand motion regardless of the hand orientation at the time the preprogrammed routine is executed.

The ACC executes the VAL language, an interpretive language which resides in 16K EPROM. At the user level, VAL is based on common English language words, such as "move," "draw," etc., simplifying program development.

The SCC uses the RT-11 operating system, and executes programs written in FORTRAN or assembler language. Communications between the ACC and SCC scanning of the tactile sensor, and other utility functions are done by assembler language subprograms. Quantitative processing of arm position and sensor information can be done in FORTRAN. It should be noted that the SCC and ACC work asynchronously, and while the SCC is processing data the ACC is still controlling the arm.

To conclude this section, the nut removal task discussed in Section II will be pursued further. In Section II, the hand was aligned with the bolt axis (Figure 3). The second phase of the task is to actually determine the location of the axis. This may be done using the tactile sensor as follows (see Figure 9):

1. After alignment, the human can instruct the SCC to execute the "LOCATE" routine. The SCC then prompts the operator to switch to computer mode.

2. The ACC moves the hand until one face of the jaw contacts the nut, stores this position, withdraws the jaw, then makes a contact on the opposite side. This defines line A.

3. The hand rotates 90 degrees, and two more contacts are made, thus defining line B. The SCC determines the intersection of A and B, thereby finding the axis.

If a time-delay is present, this task will likely be much more quickly done using supervisory control than manual control. In addition, a lower workload will be imposed on the human operator. The preliminary experiment confirmed this.

VII. PRELIMINARY EXPERIMENT

A preliminary manipulation experiment was performed, primarily to test the working of all of the system components. The experiment consisted of the removal of a nut from a bolt, and used both the "ALIGN" and "LOCATE" routines described earlier. In addition, a nut removal routine was developed to unscrew the nut from the bolt.

The operator viewed the task using a fixed, black-and-white TV camera and monitor, and was physically isolated from the manipulator by a partition. The task began with the manipulator hand positioned just at the edge of the camera field of vision, and randomly misaligned (pitch of plus/minus 20 degrees, yaw of plus/minus 20 degrees) relative to the table on which the nut was tightened. The task ended when the operator had successfully unscrewed the nut from the bolt and raised it away from the table surface a small amount.

The task was performed both with and without computer assistance, and at two time-delays, 0.0 and 1.0 seconds. Two replications at each of the four conditions yielded a total of eight trials. Only one subject participated in the experiment.

Under manual control, the subject used the six-axis joystick to control the manipulator throughout the experiment. Using computer assistance, the subject brought the hand near the table, then typed "ALIGN" to the SCC. After completion of the alighment routine, the subject brought the hand roughly alongside the nut and typed "LOCATE" to the SCC. After completion of this routine the hand was centered over the nut and ready for grasping. The subject then typed "NUT" and the manipulator unscrewed the nut under computer control. The LOCATE and NUT routines could be combined, but we preferred to leave LOCATE more general for future uses other than nut removal.

The completion times for this task are shown in Table 1. Although the sample sizes are much too small for statistical comparison, it is evident that supervisory control yielded lower completion times, especially at the 1.0 second time-delay. In addition, the subject reported a definite preference for the computer assistance.

VIII. CONCLUSION

This paper has described a system for the study of supervisory control of remote manipulation where control is traded between man and computer. By virtue of the excellent positional accuracy of the manipulator and the effective distribted processing architecture made possible by the VAL software of the Arm Control Computer and the FORTRAN/Assembler language of the Supervisory Control Computer, this system has the potential to accomplish sophisticated tasks. The human operator becomes a scene analyzer, planner, and supervisor. Preliminary experiments indicate that supervisory control with this system yield lower task completion times and is preferred by the operator over manual control.

Table 1

Time-Delay	Manual Control	Supervisory Control
0.0	163	113
	166	106
1.0	313	140
	280	125

Completion Times,
Preliminary Experiment

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