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Performance Experiments with Alternative Advanced Teleoperator Control Modes for a Simulated Solar Maximum Satellite Repair

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Abstract

This paper describes the experiments conducted at the JPL Advanced Teleoperator Laboratory recently to demonstrate and quantitatively evaluate the effectiveness of various teleoperator control modes in the performance of a simulated Solar Max Satellite Repair (SMSR) task. The SMSR was selected as a test task because it is very rich in performance capability requirements and it actually has been performed by two EVA astronauts in the Space Shuttle Bay in 1984. The main subtasks are: thermal blanket removal; installation of a hinge attachment for electrical panel opening; opening of electrical panel; removal of electrical connectors; relining of cable bundles; replacement of electrical panel; securing parts and cables; re-mate electrical connectors; closing of electrical panel; and reinstating thermal blanket. The current performance experiments are limited to thermal blanket cutting, electrical panel unbolting and handling electrical bundles and connectors. In one formal experiment seven different control modes were applied to the unbolting and reinsertion of electrical panel screws subtasks. The seven control modes are alternative combinations of manual position and rate control with force feedback and remote compliance referenced to force-torque sensor information. Force-torque sensor and end effector position data and task completion times were recorded for analysis and quantification of operator performance.

1. INTRODUCTION

In the last year, the Advanced Teleoperation (ATOP) Laboratory in the Robotics and Automation Section at JPL developed the ability to perform selected sub-tasks of a satellite repair operation with remotely operated manipulators. We chose the Solar Max Satellite Repair (SMSR) performed in an Extra-Vehicular Activity (EVA) by astronauts in 1984 as a model to demonstrate our capability. Our current capabilities of picking up tools for the repair operations, cutting taped seams of the thermal protection blanket around the Main Electronics Box (MEB) panel of a mock-up of the satellite, and removal and reinsertion of screws holding down the MEB panel enabled us to carry out a series of experiments to study operator performance with the alternative manual control modes and system parameters available on our system. A recent experiment we conducted and the results from it are reported in detail in this paper.

The history of operator performance evaluation with manual control modes in remote manipulation stretches back to the 1940's[14]. We have noted the lack of statistical rigor in much of the previous work in this field and results quoted have been mainly by visual inspection. This has been possible in simple experiments when differences are obvious in the data. It is widely accepted that position control without force feedback has faster completion times than both resolved motion rate control and joint rate control[10][11][15]. Means task completion times with pure position control were found to be 3-4 times better than with resolved motion rate control which, in turn, was 2-3 times better than joint rate control[11]. The advantages of resolved motion rate control were confirmed[6] for large workspace and limited manipulator speed and non-contact situations in task completion time. However, for small workspace applications, position control was found to be a better mode of operation. A recent study showed that position with shared compliant control [5] generated less interaction forces than position with force reflection on a telerobot. Performance measures used in the study were task completion times, cumulative forces of interaction and task board contact time. In this current work, statistical analysis has been applied rigorously to the data and we quantify the differences with probabilities that one manual control mode is better than another for specific performance measures.

2. ADVANCED TELEOPERATION SYSTEM

Detailed descriptions of components of the ATOP system have been reported elsewhere [1][2][12][13]. We briefly overview the important aspects of the system for completeness.

2.1 Master-Slave System

In the full configuration, the ATOP system is a dual-arm system [13]. We used a single arm (the right side of the system) in this study. On the master side is the 6 axes force reflecting hand controller. Switches on the FRHC allow the operator to activate and deactivate robot control. Incremental commanded motions of the FRHC are relayed to the slave. In manual position control mode, the operator is able to cover the larger workspace of the robot with the limited workspace of the FRHC by indexing. Inverse kinematics is not necessary on the FRHC side because hand controller joints approximate a cartesian coordinate frame and the operator automatically compensates for the small errors that occur.

A PUMA 560 robot with 6 degrees of freedom is used as the slave and a JPL Smart Hand [1] with a 6 axes force/torque sensor (F/TS) is used as the end effector. The 2-jaw gripper on the hand is used for holding the tool used in this experiment. Sensors on the hand also measure gripper jaw positions and forces. Local and remote sides are separated by a wall with one window that was kept obscured by a black curtain during the experiment.

2.2 Visual Feedback System

Six video display terminals are available for visual feedback to the operator in the full configuration of the ATOP system. However, only three were used in this experiment to display video images from cameras located in the remote side. The three camera image displays (identically used for all manual control modes in this study) are arranged beside each other in a console facing the operator: The terminal on the right shows the view from the camera placed to the right of the task board with a right side view of the task board; the terminal in the center shows the image from the overhead camera looking forward and down on the task board; and the terminal on the left shows the image from the camera facing the task board and from the rear of the robot. Two cameras, the camera at the back and on the right are mounted on pan and tilt units and can be controlled from the local (operator) side of the system. In addition, on those two cameras, zoom, focus and iris are also controllable from the operator side.

The telerobotic configuration editor (TCE) [9], an iconic interface used for selecting configuration parameters, setting gain values, and control modes, was programmed for the alternative control modes under study. It was used by the experimenter for quickly alternating between the various control modes during the experiment, as required by the randomization of the tasks presented in our experiment. The TCE interface was repositioned so that it was not directly visible to the subjects during the experiment.

2.3 Operator Control Station

The configuration of the operator control station is as shown on Figure 2.1. The three upper displays were not used by the subjects during the experiment. The subjects were seated to the left of the hand controller and faced the console. Two foot switches on the floor were used to control the tool, one for unbolting and the other for bolting the screw. Lighting in the control room was turned off for better visibility of the display terminals.

2.4 Task Board and Tools

The task board consists of a mock-up of three sides of the Solar Maximum Satellite consisting of 5 panels, the MEB and its 4 adjacent panels. The MEB panel, on-loan from NASA Goddard Space Flight Center, is an accurately scaled flight replica of the panel used on the satellite. The remaining panels and the frame holding all the panels were built in-house. Thermal protection blanket, consisting of gold Mylar film on a thin foam sheet, covered the mock-up. In this experiment, the MEB panel face is exposed, simulating the completion of the first phase of the satellite repair procedure of cutting and folding back of the blanket. The configuration of the task board and the relative location of the side and front view cameras are shown in Figure 2.2.

The tool used in the experiment was a modified power screwdriver operated by the subjects with foot switches located in front of the operator seat in the control room. The tool has a handle attachment to provide a firm grip in the jaws of the JPL Smart Hand. While not in use the tool is held on the tool caddy with Velcro tape.

3. EXPERIMENTS

Three operator performance experiments have been conducted to-date on the ATOP system. In the first experiment, a comparison between manual position control with force reflection and manual position control without force reflection as alternative modes of control of the master-slave system was performed. The SMSR sub-tasks of tool pick-up, thermal protection blanket tape cutting, and MEB panel screw removal were the tasks performed in the experiment[3]. In the second experiment[4], the same sub-tasks were performed with visual feedback images from three black-and-white (B+W) cameras placed in the remote site (displayed on three monitors in the control room) compared to operator performance with an image from a stereo-pair of B+W cameras at the remote site (displayed on a single monitor). The most recent in the series of SMSR experiments in the ATOP has been the comparison between seven alternative manual control modes in the performance of the screw unbolting and bolting of a MEB panel screw and in the remainder of this paper, this experiment is described in detail.

3.1. Task

The task selected was socket head screw removal and reinsertion. The steps in the execution of the task are:

1) move in a straight line forward (1.25" in the positive x direction) to bring the tool bit to the head of the socket screw.
2) engage the tool bit with the screw head.
3) unscrew by activating of the *unscrew* foot switch while withdrawing the tool as the screw unbolts.
4) withdrawal to approximately the start position after the screw was free of the threaded part of the screw hole,
5) return to the location of the hole.

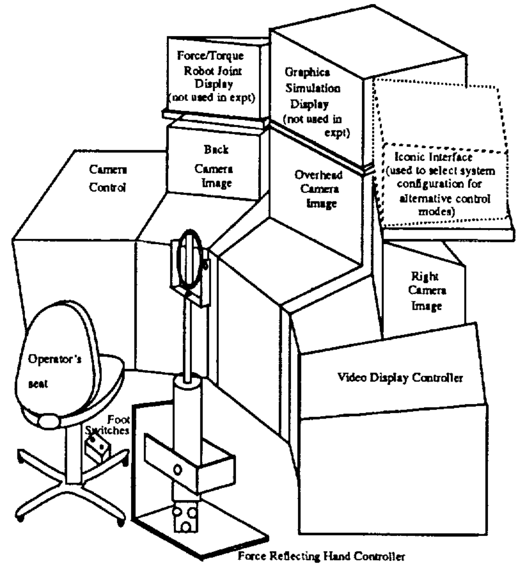

Figure 2.1 Operator Control Station

6) reinsertion of the screw by activation of the *screw* foot switch.

During the withdrawal phase the screw remained attached to the magnetized bit of the tool unless external forces or motion of the tool unseated it.

3.2 Experiment Design

A completely randomized single factor, within subject (repeated measures) design was specified for this experiment. The single factor represents the independent variable "control modes", and its seven levels correspond to the seven control modes described in Section 4. Seven subjects participated in the study. The presentation order of the seven control modes was randomized for each subject. Each control mode was presented three times, and so in all, every subject had to perform the task 21 times (i.e. 3 repetitions times 7 control modes). Seven dependent measures, described in detail in the following section, were defined on each subject. A training procedure, described in Section 4.1, was planned to reduce within-subject and between-subject variance without an extended training period.

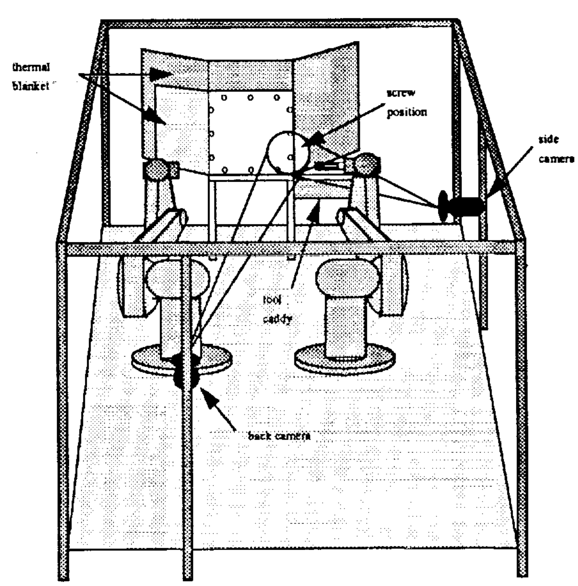

Figure 2.2 Remote Environment

3.3 Dependent Variables

The seven dependent measures in the experiment were:

1. Average Completion Time, the mean time it took to successfully complete the task.
2. Average Force, the mean force exerted by the end effector on its environment during the contact phase alone.
3. Average Torque, the mean torque exerted by the end effector on its environment, during the contact phase alone. The Average Force or Torque value is computed using

$$AverageForce = \frac{\sum_{i=1}^{N} f_i}{N}$$

where N = number of data samples in the contact phase, f_i was the magnitude of i^{th} force or torque vector. The force magnitude is defined as

$$f_i = \sqrt{f_{xi}^2 + f_{yi}^2 + f_{zi}^2}$$

where f_{ni} was the n^{th} component axis (x,y,z) for the i^{th} sample of force. The equation for the torque is similar, replacing the translational axes (x,y,z) with the rotational ones *(roll, pitch, yaw)*.

4. Cumulative Task Force, the time interval summation over the contact time of the forces exerted by the end effector on its environment multiplied by the sampling interval.
5. Cumulative Task Torque, the time interval summation over the contact time of the torques exerted by the end effector on its environment multiplied by the sampling interval. The equation for the Cumulative Task Force and Cumulative Task Torque measures goes as follows:

$$CumulativeTaskForce = \sum_{i=1}^{N} f_i \Delta t$$

where N= number of data samples in the contact phase, f_i is the magnitude of the i^{th} force or torque vector, Δt *sec* = the sampling interval. Cumulative Task Torque is computed similarly.

6. Number of Errors, the errors were defined as either a drop of the screw, or having to "recover" more than twice during task execution. A recovery was defined as a re-engagement followed by turning of the screw after accidental loss of engagement.
7. Subjective ratings of control modes by the subjects based on their collective experience with the alternative control modes. The score was obtained by having the subjects indicate on a scale of 1 to 9 their rating of each control mode with 9 being the best and 1 the worst.

The first five dependent measures above have historically been used in the ATOP laboratory to evaluate operator performance. Although it is not clear if these measures are the best way to characterize operator performance, intuitively, they do measure variables of interest and a cost can be attached to poor performance according to these variables in space applications; time spent in space is very expensive and excessive force/torque exertion can damage delicate instruments. Also, task completion time has been used by all previous researchers in the field so it should serve as a measure for comparison of our results with those quoted in the literature.

The cumulative force/torque measures combine task interaction forces/torques with contact time. It is possible and it would be interesting to combine the respective elements in different weightings to but that would require an experiment designed for that purpose and we have not elected to perform such an experiment yet.

3.4 Manual Control Modes

All control modes described below are closed-loop due to visual feedback to the operator. However, the terms open-loop and closed-loop have been used to indicate whether kinesthetic force feedback to the operator is used for manual control.

3.4.1 Position Control without Force Reflection or Compliance (PNA)

This is essentially an open-loop manual control mode in which the operator commands robot position relying only on visual feedback, and not on a kinesthetic force feedback via the FRHC. There is no force reflection or compliance added to the system as shown in Figure 3.1 It should be noted that although the stiffness of the robot is large when maintaining a commanded position, it is not infinite due to the finite control gains implemented on the robot PD joint controllers and saturation limits of joint actuators.

3.4.2 Position Control with Force/Torque Sensor (F/TS)-Based Force Reflection (PWF)

Here is a closed-loop manual control mode whereby measurements from the F/TS on the robot hand sampled at 1KHz are used to drive the FRHC. The control architecture is illustrated on Figure 3.2. .

3.4.3 Position Control with Remote Side Compliance (PWC)

In this open-loop mode of manual control, position commands from the FRHC are used to drive the slave robot. However, compliance implemented on the robot modifies the operator commanded positions to the robot causing it to yield to task interaction forces. The low pass filtered force and torque control loop in the remote site emulates a damped spring connected to the robot hand for each cartesian axis. The slave manipulator is thus made compliant to external forces and torques. This so-called shared compliance control [7] architecture is shown on Figure 3.3.

3.4.4 Position Control with Position Error Based Force Reflection (PEF)

The PEF control mode is described in [8]. The essential feature of this closed-loop mode is the implementation of compliance on the slave robot, and using the position error, generated during any force interaction with the task due to the compliance, to drive the FRHC. Position errors are transformed to kinesthetic feedback to the operator. Figure 3.4 below illustrates the method. It was found that this control architecture was able to generate much greater force reflection ratios than those used in the F/TS based force reflection mode (PWF), while maintaining system stability.

3.4.5 Rate Control without Force Reflection or Compliance (RNA)

This control mode is rate without force reflection or compliance as shown on Figure 3.5. This is the traditional resolved motion rate control mode used extensively in manual control.

3.4.6 Rate Control with F/TS-Based Force Reflection (RWF)

In this control mode, illustrated in Figure 3.6, force/torque measurements from the sensor on the robot hand were added to the spring/damper force implemented for manual rate control. With this control mode, close to the home position of the FRHC, subjects could feel forces/torques corresponding to sensor readings but as they moved away from the home position, the spring force returning the FRHC to its home position would become significant enough to prevent discrimination between the spring force and the reflection force. This is a combination that has not been attempted elsewhere. The force reflection gains were identical to those used in the position control with F/TS force reflection. A local side PD controller is used to implement the spring/damper effect common to rate control input devices.

3.4.7 Rate Control with Remote Side Compliance (RWC)

Remote side compliance with identical gains to those used for position control with remote compliance was implemented in this control mode. The control architecture was as shown on Figure 3.7. The subjects had to rely on visual feedback alone for performing the task in this control

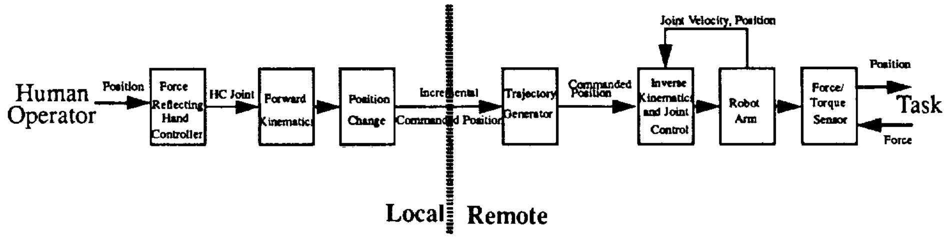

Figure 3.1 Position Control without Force Reflection or Remote Side Compliance

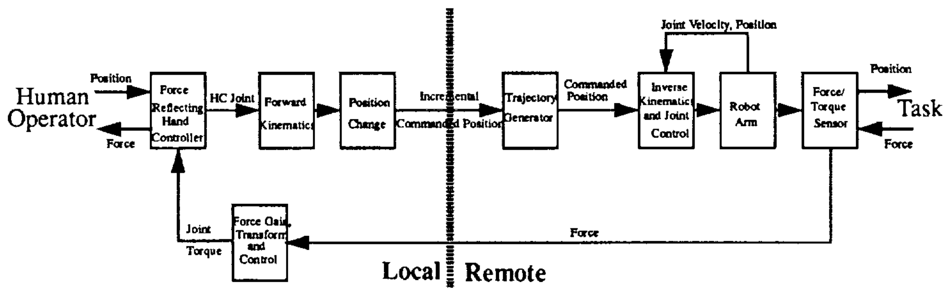

Figure 3.2 Position Control with F/TS Based Force Reflection

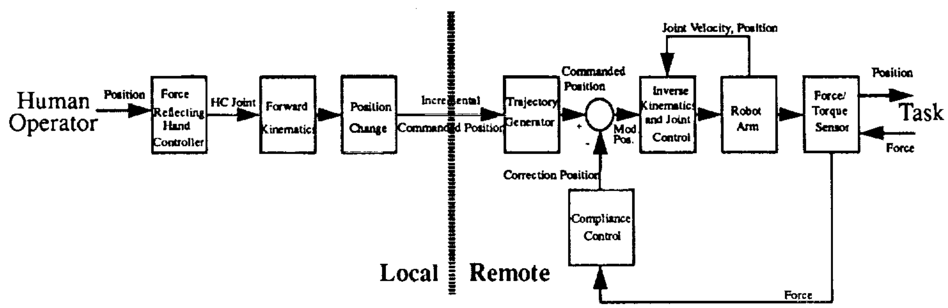

Figure 3.3 Position Control with Remote Side Compliance

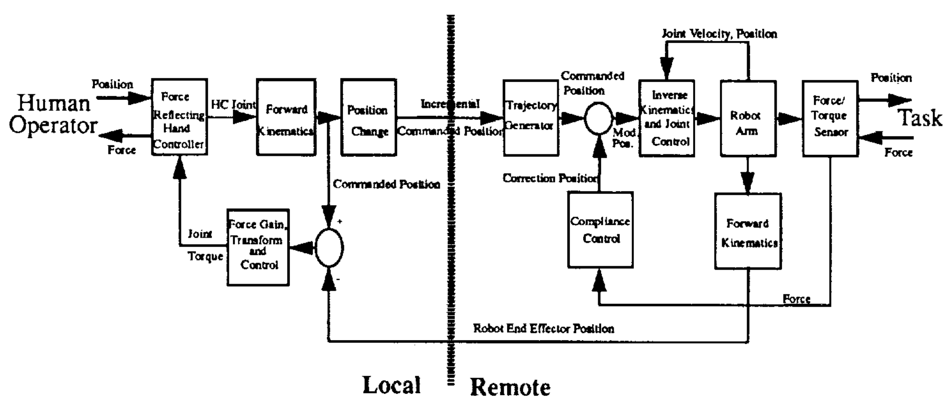

Figure 3.4 Position Control with Position Error Based Force Reflection

mode.

4. EXPERIMENT PROCEDURE

4.1 Subject Training

Teleoperation, by its nature, is a complex operation, requiring the timely integration of many sensory, cognitive, and motor inputs and functions by the operator, in order to achieve a satisfactory level of performance. Proficiency in teleoperation is thus largely a function of training. We believe that there is evidence to support hypothesis that the training period may vary (according to task complexity) from a few days to weeks or even months before a leveling off of the performance curve occurs.

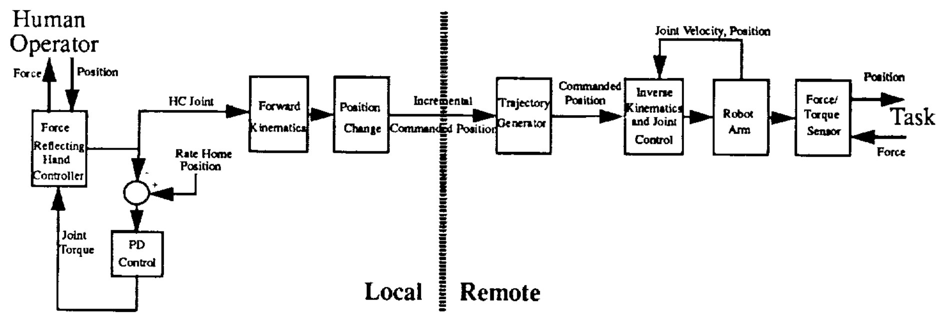

Figure 3.5 Rate Control without Force Reflection or Remote Side Compliance

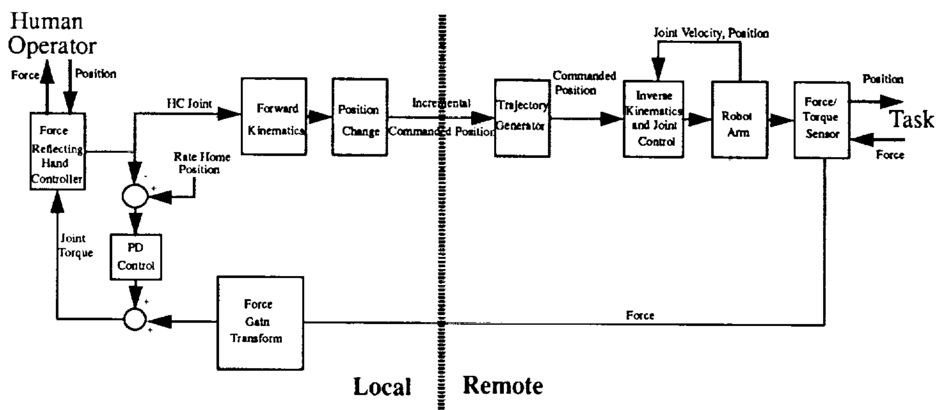

Figure 3.6 Rate Control with Force/Torque Sensor Based Force Reflection

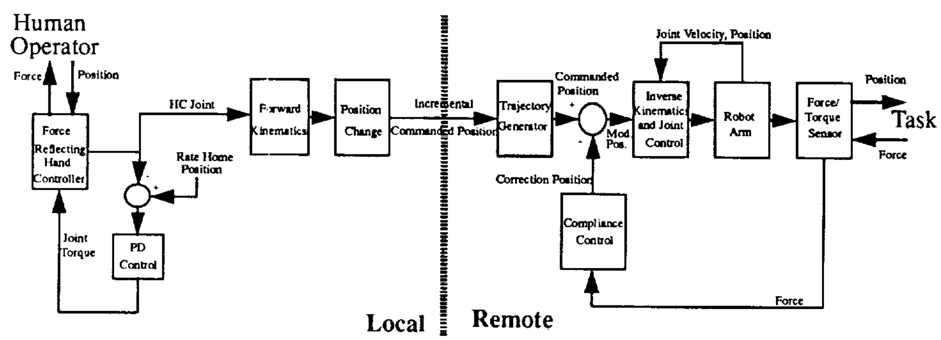

Figure 3.7 Rate Control with Remote Side Compliance

In this experiment, due to time constraints, instead of training subjects until they reached their level of proficiency, a criterion was established to denote the end of an individual's training period. This criterion stated that an individual had reached the end of his/her training whenever the ratio of the standard deviation to the mean of performance for five consecutive trials was 0.15 or less. By doing so we managed to provide all subjects with comparable training that resulted in reduced within-subject variance and between-subject variance.

Since in most cases several days had elapsed between the completion of training and the onset of the experimental session, subjects were required to perform the task successfully once for each of the control modes at the beginning of the experimental session. The data from this practice run was not used in the evaluation of performance.

4.2 Data Collection

Data collected during the experiment were: *x, y, z, pitch, yaw* and *roll* positions of the robot end effector in a world coordinate frame, *x, y,* and *z* forces and *pitch, yaw* and *roll* torques sensed by the F/TS resolved to a world coordinate frame, and end effector gripper jaw positions and forces. Each variable collected was sampled at 1000Hz then averaged over 16 samples before being stored in real-time during the experiment on a personal computer (PC) dedicated for data collection. Each stored value of a variable thus represented the average value of the respective variable over 16 milliseconds.

4.3 The Experimental Run

The chronology of an experimental session was as follows:

1. The subject was instructed on the procedure and the objectives. Instructions given to the subject at the start of the experiment were:
   a. Perform the task as quickly as you can.
   b. Try to exert minimal force and torque.
   c. Avoid committing errors.
2. The subject was given a practice run with each of the seven control modes in succession to re-familiarize himself with the modes.
3. The subject was asked to read the rating questionnaire to be filled after the end of the session.
4. The experiment was started and data was collected for each run. The

subject was informed of the control mode he was about to operate with prior to each run, so that he would know what to expect. The experimenter started each experimental run with a countdown to synchronize the subjects's start with the manual activation of the data collection program. The task was judged complete by the experimenter when the tool bit stalled at the end of the screw reinsertion phase at which time the data collection program was stopped. Three main functions performed by the two experimenters during the experiment were:

a. manual activation and deactivation of the computerized data collection system at the start and the end for each run by pressing a key on the computer dedicated for data collection,

b. re-configuration of the teleoperation system for the next run, and

c. observation and manual recording of any errors and other exceptional events occurring during each run.

5. At the end of the session, the subject was asked to fill out the questionnaire rating the different modes.

The experimental sessions including rest periods lasted about 2 hours for each subject.

5. RESULTS

Table 5.1 contains the means and standard deviations of subjects' performance for the seven measures: the completion time, the average force and torque, the cumulative contact force and torque, the no. of errors, and the subjective ratings of the control modes. Three major hypotheses were tested for statistical significance using the Multivariate ANOVA procedures [16]. However, visual inspection of the data plots can offer a wealth of valuable qualitative observations. These are not subjected to rigorous statistical testing in order to keep the experiment-wise error (experimentwise α) [16] from inflating.

5.1 Visual Inspection of Data

Means and standard deviations for the respective performance measures are plotted on Figure 5.1a-g and listed on Table 5.1. Ranking the seven

Table 5.1: Means (Standard Deviations)

control mode	average time	average force	average torque	cum. task force	cum. task torque	no. of errors	subject ratings
PEF	57.62 (5.82)	3.03 (0.32)	0.83 (0.13)	13.47 (6.78)	3.82 (2.32)	0.43 (0.79)	6.86 (1.35)
PWC	67.05 (11.04)	6.25 (2.30)	1.28 (0.43)	127.83 (105.17)	23.86 (14.50)	0.43 (0.54)	6.14 (0.69)
PWF	70.80 (19.87)	7.79 (1.87)	2.05 (0.41)	207.47 (88.61)	53.62 (21.11)	0.43 (0.79)	6.71 (1.11)
PNA	75.40 (15.07)	10.37 (2.12)	2.76 (0.55)	342.01 (97.10)	88.46 (27.02)	0.14 (0.39)	5.00 (1.00)
RWF	101.36 (15.57)	12.91 (3.44)	2.59 (0.44)	574.66 (110.82)	117.99 (25.43)	0.57 (1.13)	3.86 (0.90)
RWC	108.94 (67.36)	10.41 (2.98)	1.44 (0.28)	385.52 (245.39)	59.63 (44.09)	0.86 (1.46)	3.57 (1.13)
RNA	144.12 (49.80)	15.59 (2.56)	2.62 (0.42)	1086.94 (382.30)	198.05 (104.17)	0.86 (0.69)	2.29 (1.25)

control modes based on the data plots results in the PEF being always the best followed by PWC, while RNA is always the worst, with RWF being the next worst. In the middle, PWF, PNA, and RWC interchange their rank as a function of the measure being looked at.

Standard deviations are greatly reduced with the PEF condition in all five measures, but generally they are comparable for all control modes, in terms of both average force and torque measures. This is not the case for completion time, where in the rate modes (excluding the RWF) the variability in performance was much larger than in the position modes. The cumulative task force and torque plots also indicate that there exists a larger variability of performance in the rate modes than in the position modes.

Compliance appears to be better than the F/TS force reflection in both rate and position modes, in terms of the force/torque indices, however compliance does not appear reduce completion time.

RWC was the only rate mode capable of matching and even outperform-

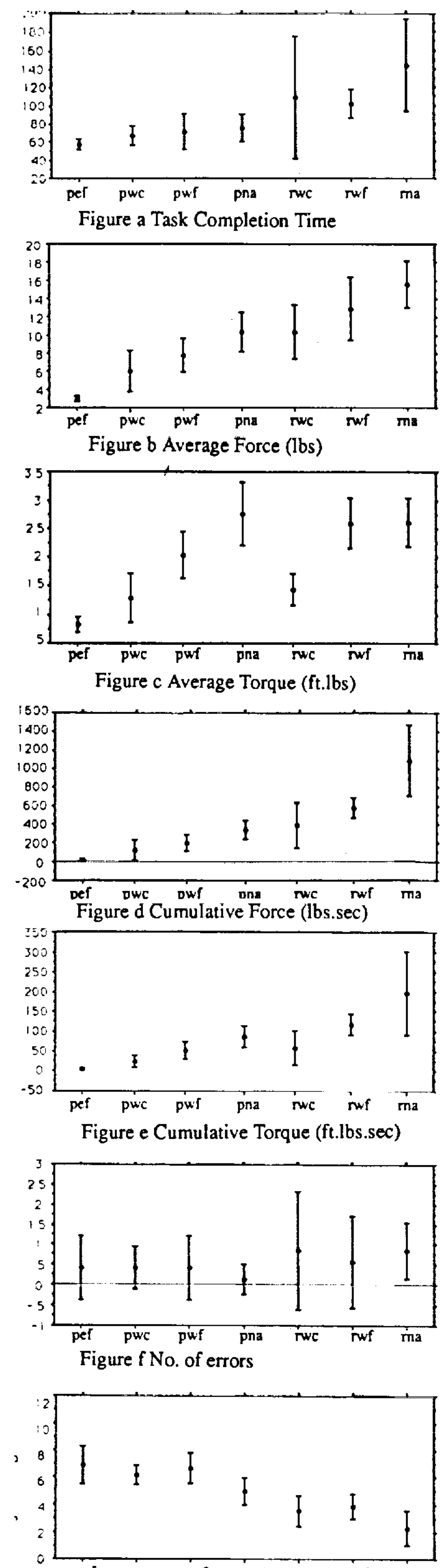

Figure a Task Completion Time

Figure b Average Force (lbs)

Figure c Average Torque (ft.lbs)

Figure d Cumulative Force (lbs.sec)

Figure e Cumulative Torque (ft.lbs.sec)

Figure f No. of errors

Figure g Subject Ratings

Figure 5.1 Means and Std. Dev. for Respective Dependent Measures ing some of the position modes, albeit only with respect to the force and torque measures.

Inspection of the remaining data plots (Figures 5.1f, g) reveals that the number of errors did not prove itself as a particularly sensitive measure of performance, mainly due to the fact that there was great variability in performance for that measure, in all the control modes.

On the other hand, subject ratings clearly indicates a general preference of position modes over all rate modes. Ranking of the control modes based on subject ratings yielded the PEF as the favorite control mode, with PWF and PWC following closely. PNA was the least favorite among all position modes. The order of preference for rate control was RWF, followed closely by RWC and RNA. The fact that subjects preferred the F/TS force reflection modes over the compliance modes, contrary to the ranking of these modes by other performance measures (average force and torque, cumulative task force and torque) suggests that the "objective" performance measures may not be adequate in some sense. An explanation may be the loss of operator control (the remote manipulator has a semi-autonomous behavior in its response to external forces/torques) when compliance is implemented and the subjects may have preferred the feeling of being-in-control even at the cost of poor performance.

5.2 Hypotheses Testing

Results of the analysis are summarized in Table 5.2. The following three hypotheses were formulated for testing with the Multivariate ANOVA (evaluating the Wilks' Lambda Statistic, R), on the first three performance measures:

1. The first hypothesis tested that there was no difference in the means of performance between the position and the rate control modes. Analysis shows that R=7.63, with probability, p=0.04, a significant difference between the means of performance in the position modes and the rate modes, in favor of the position control.
2. The second hypothesis tested was that the newly implemented control mode, PEF, was not better than the best among all other position modes, PWC. Testing resulted in R=6.56 and p=0.05, a significant difference in favor of the PEF control mode.
3. The third hypothesis compared the two traditional control modes, i.e. pure position control with no force reflection or compliance (PNA) against pure rate control (RNA). Analysis yielded R=7.88, with p=0.04, a significant difference in favor of the position control mode.

Table 5.2 Multivariate ANOVA Hypothesis Test Results

HYPOTHESIS	MULTIVARIATE ANOVA WILKS' LAMBDA (R)	DF	P
1. Position vs. Rate	7.63	3,4	0.04
2. PEF vs. PWC	6.56	3,4	0.05
3. PNA vs. RNA	7.88	3,4	0.04

6. CONCLUSION

In this paper, we have demonstrated several points:

1. Position control modes yield better overall teleoperation performance than rate control modes, and were preferred by operators. We should note that training, which took a significantly longer time than actual experiment time, probably affected the perception of the subjects on their preferences. We have not analyzed the training data to discern trends similar to those obtain from the experiment.
2. Position error based force reflection with compliance implemented on the remote side is the best of all control modes in this study. This finding can be attributed to improved force reflection ratio alone. However, disadvantage of this mode is that the feel of the FRHC is sluggish and force feedback is slightly delayed due to the very limited bandwidth of the force reflection.
3. If one were to choose between operating with the pure position control mode and the pure rate control mode in situations were contact and dexterity are the main requirements of performance, there is little doubt that pure position control is preferred.

In addition we have observed the advantage of compliance over the F/TS force reflection in terms of improved force/torque management performance, although subjects indicated in their subjective ratings a slight preference for the force reflection modes. However the advantage of FT/S force reflection over the pure position and rate modes is apparent in terms of most measures.

While our conclusions mostly apply to the selected sub-task of the SMSR, screw removal and re-insertion, under our experimental conditions and for our performance indices, we do believe that they can serve as a guide for recommendations in similar real or simulated teleoperation situations.

7. ACKNOWLEDGEMENT

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