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Task-Level Testing of the JPL-OMV Smart End Effector

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1. ABSTRACT

An intelligent end effector previously developed at JPL has been tested in over 21 hours of experimental teleoperation. The end effector provides local control of gripper clamping force and a 6-degree-of-freedom, wrist mounted force torque sensor. Resolved forces and torques were displayed to the test subjects, and the effect of this information on their performance of simulated satellite servicing tasks was assessed. The experienced subjects accomplished the tasks with lower levels of RMS forces than intermediate and naive subjects, but the force levels were apparently uncorrelated with the presence or absence of the display. This negative finding was attributed to the lack of a suitable control mode in the manipulator control system.

2. INTRODUCTION

Future operations in space such as satellite servicing, refueling, and construction will rely extensively on teleoperations. Teleoperations will also serve as a vital backup capability for any currently conceivable level of autonomous robotic functions. To support these applications work is focusing on improving the interface between operator and manipulator. Important variables at this control interface are the forces and torques exerted by the operator.

The Applied Robotics and Teleoperators group at JPL has recently developed a new intelligent end effector for testing with human operators in a simulated satellite service task. The JPL-OMV Smart hand (1,2) is equipped with a 6-dof force-torque sensing wrist and display system, as well as microprocessor control of gripping force. The system thus provides for controlled gripping of delicate objects, and feedback of force-torque information to the operator for avoiding jams and dangerous stresses on manipulated objects.

Recently, the system has been mounted to a manipulator arm and tested with human operators performing simulated satellite servicing tasks. Testing consisted of recording forces and torques from the wrist and jaw mounted sensors while operators performed tasks by teleoperation from the remotely located control station. Tasks consisted of connecting and disconnecting a fluid coupling, simulated module changeout, and attempting to exert constant forces and torques on the environment. Operators performed the tasks both with and without the force torque display.

Because of the nature of the tasks, a lack of complete information on the manipulator state and design parameters, and the variations inherent in man-in-the-loop systems, the analysis of the force/torque data presented here tends towards the descriptive and anecdotal. However, a quantitative look at task performance is provided by reduced measures such as root-mean-squared (RMS) and Sum of Squared (SOS) forces and torques.

3. SYSTEM DESCRIPTION

3.1. Smart Hand Hardware

The JPL-OMV Smart hand is a one degree of freedom gripper with intermeshing jaws consisting of parallel plates with a V grove section. Each jaw is instrumented with its own load cell to measure gripping force. The jaws are driven by a DC motor via opposing lead screws.

The entire mechanism is mounted to the manipulator wrist through a 6-dof strain gauge load cell by which interaction forces and torques are measured. Three microprocessors are mounted in the hand for motor control, strain gauge data acquisition and processing, and communication. Thus, the command interface and force torque feedback require only a single full duplex RS-232 link between the hand and the support equipment.

A support chassis provides power for motor and electronics, and another microcomputer for high level control and force torque display. A control box is provided for operating the hand. The control box has controls to set the gripper control mode; to give force, rate, and position commands; and to set operating parameters such as force and rate limits.

3.2. Smart Hand Control Software and Display

Force and torque servoing of the gripper motor takes place entirely in the hand itself using the motor control micro-processor. Commands from the control box are sent to the

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motor controller via the serial link and the communication processor.

Force and torque information is continually sent to the support chassis for display by graphics hardware on a CRT. The forces and torques are represented as bar graphs in a star configuration (figure 1) which suggests a perspective view of the end effector coordinate frame. The software provides two adjustments for the display: 'bias' and 'Fmax'. The bias command memorizes the current levels of forces/torques, and subtracts them from subsequent values before display. This allows strain gauge offsets and constant forces such as gravity not to be displayed. Fmax, sets the magnification of the display by specifying the force or torque level corresponding to a full bar-graph display. The default value of Fmax is 100 lb for testing with human operators, we consistently set Fmax to 20 lb which permitted smaller forces and torques to be resolved on the display.

4. METHODS

4.1. Testing Protocol

Testing was performed at the Marshall Space Flight Center, Huntsville, AL, using the smart hand attached to the Prototype Flight Manipulator Arm (PFMA) (3). The PFMA is a 6-dof arm with a maximum reach of about

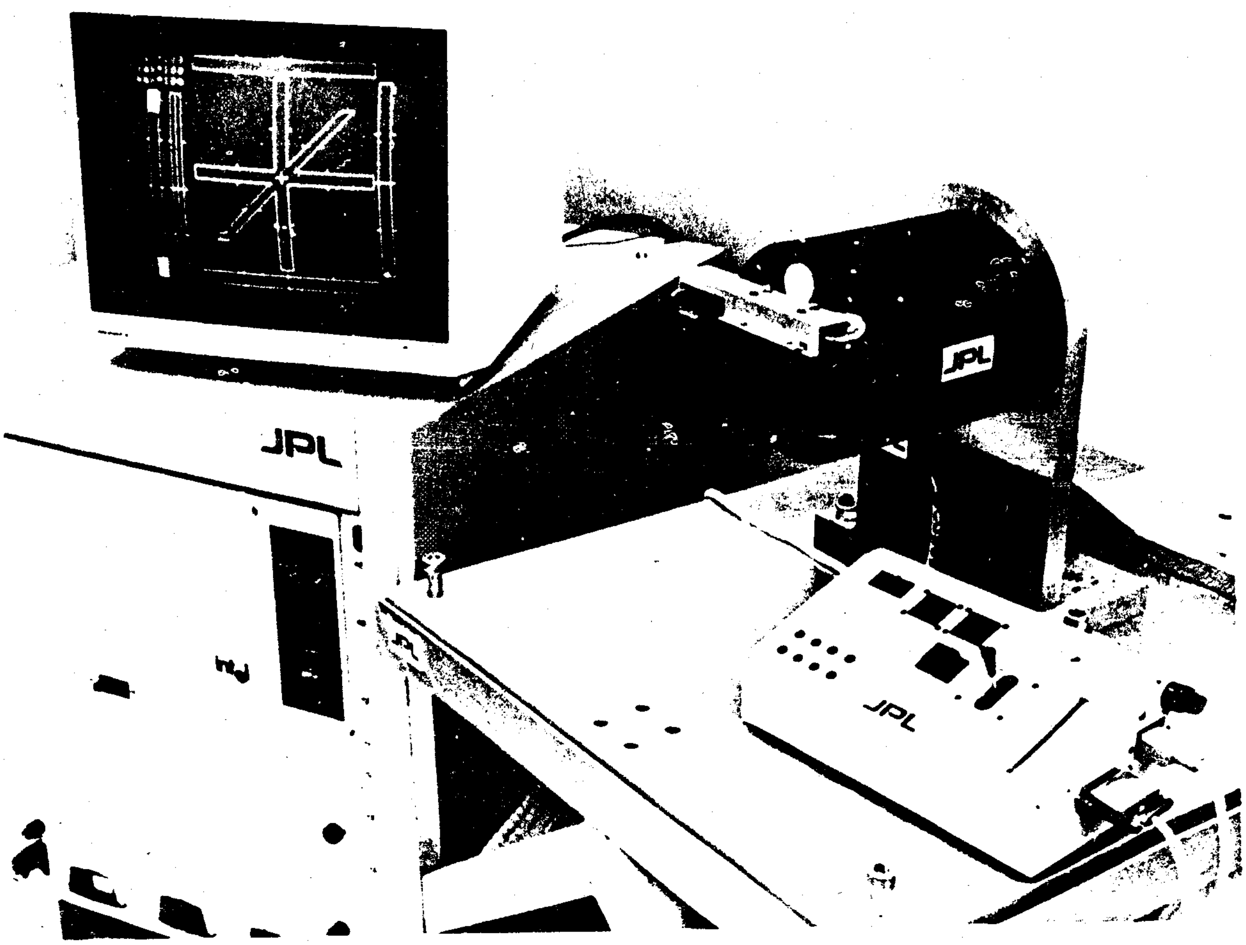


Figure 1.

[illegible]

9 feet. The PFMA was designed for 1G and 0G testing of autonomous and teleoperated robotics procedures and devices. For ground based testing, removable counterweights are provided.

Teleoperation was set up from a control room across the hallway. The operator viewed the workplace with three television cameras. Two remote controlled pan-tilt-zoom closed circuit cameras were located just outside the task defined work volume, one aiming parallel and one perpendicular to the task board. A miniature charge coupled device color camera was mounted on the wrist of the robot arm. The operator viewed the television signals on three monitors, two directly in front of and below the line of sight in the control console, and one on a large projection television set directly in front and slightly elevated. Operators controlled the PFMA via task space rate commands given by manipulation of the 6-dof 'joyball' hand controller produced by CAE electronics of Canada.

Subjects first observed the task board and experimental setup in person. In addition to general familiarization with the task, the subjects were instructed in the meaning of the force torque display, and exerted forces and torques on the end effector jaws with their hands while observing the resulting display.

4.2. Tasks and Subjects

4.2.1. Tasks

The tasks performed were largely determined by the task board accompanying the PFMA (3). In order of the amount of data taken, the tasks were:

4.2.1.1. The Purolator fluid coupling

This consisted of removal of the fluid coupling from its storage socket, translating to another female fitting, and inserting the connector. The connector was removed by grasping the handle, rolling the connector approximately 100 degrees, and pulling straight back. Insertion was the opposite sequence.

The difficulty in this task lay in precise alignment of the connector to avoid jamming. The task was repeated with and without the force/torque display.

4.2.1.2. The Module Changeout (Box)

This task consisted of removal and insertion of a box shaped module mock-up from a close fitting chamber. This task was also sensitive to jamming.

4.2.1.3. Generic Force Control Task (Pushing)

This task consisted of applying constant forces and torques of various magnitudes against a stationary object such as the task board surface (forces) or the handle of one of the task board devices in its holder (torques).

5. Subjects

Experimental subjects were employees of the Marshall Space Flight Center. Their experience level varied from administrative employees with no technical experience, to engineers who worked with and maintained the manipulator and task board on a daily basis. Intermediate subjects had used the manipulator in previous experiments.

5.1. Instrumentation and Data Recording

During task performance, strain gauge information was sent via serial link to a personal computer which collected the data and recorded it on floppy discs for later analysis at JPL. Data collected were the raw strain gauge signals from the wrist and jaw mounted sensors.

5.2. Analysis Software

Data analysis at JPL consists of computer processing to validate, calibrate, and resolve raw data recordings, graphics software for plotting of forces, torques, and gripping force as a function of time, and data reduction programs which compute rough measures of force control performance (RMS and Sum of Squares force signals).

6. RESULTS

6.1. Real Time Data Recording During Task Performance

The first step of data analysis produced plots of the precise time history of gripper opening; gripping force; x,y,z force; and roll, pitch, yaw torques sensed at the wrist.

Over 21 hours of experimental teleoperations resulted in a tremendous amount of data. The first level of analysis then is to present selected task recordings graphically and observe what we can from them. From there we can proceed to reduce the data and compute quantitative measures.

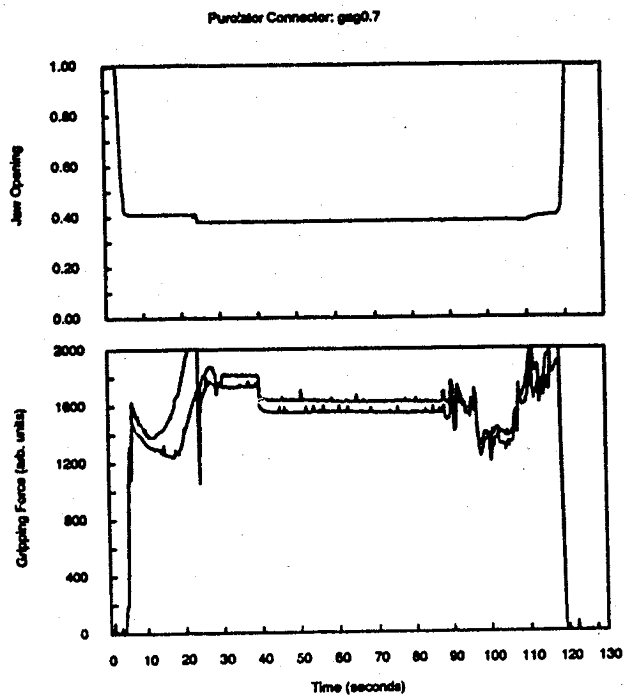
6.2. Purolator Fluid Coupling Task

6.2.1. Experienced Subject

The first data set is for an engineer who worked on the manipulator system and had considerable operating experience with the arm (with another gripper). The gripper opening and force/torque data from this subject performing one repetition of the fluid coupling removal - translation - insertion task is shown in figure 2abc.

The Jaw Opening trace shows that data recording began just before the operator closed the gripper down on the handle preparatory to removal. Clamping force immediately increases to about 1600 units (full scale of 2000 is 100 lb), but soon varies as forces are applied to the handle during removal. The force traces show two separate regions of activity corresponding to removal and insertion of the fluid coupling. These sharp boundaries make it easy to segment the data record into removal, translation, and insertion phases.

High force levels (forces in the neighborhood of 50 lb were common) were frequently encountered in this and almost all of



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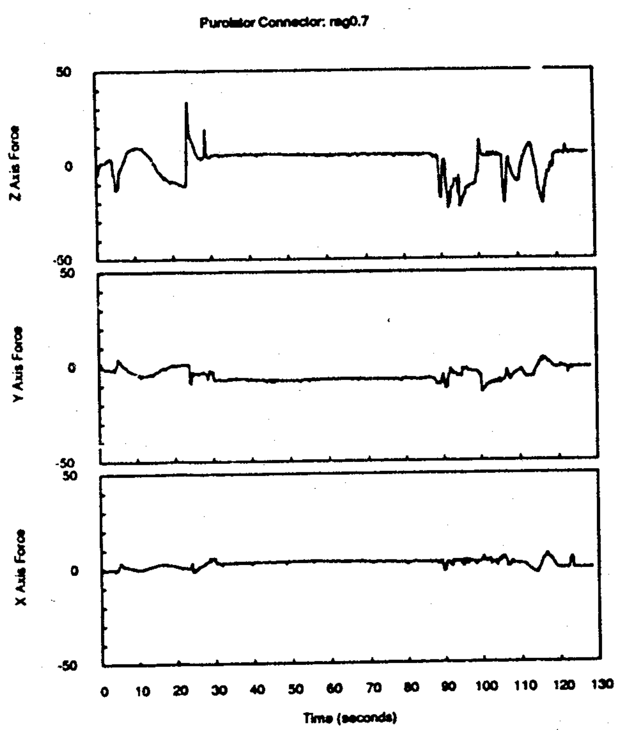

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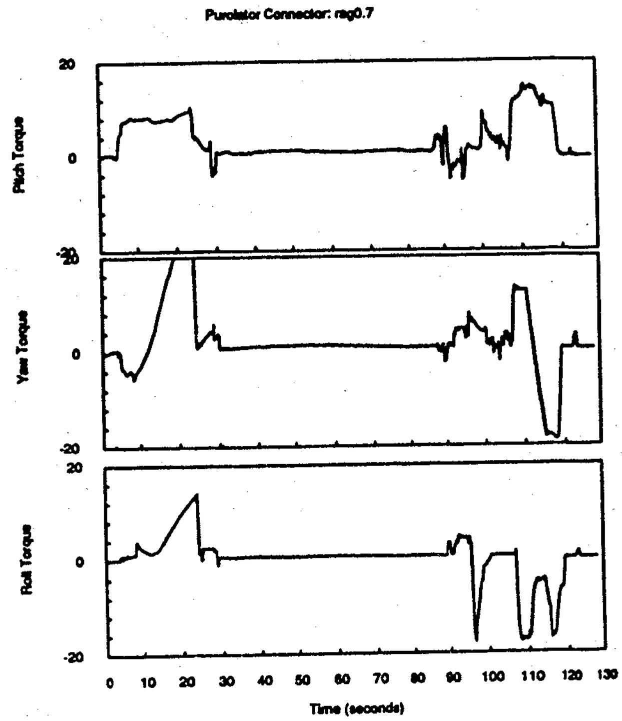


(c)

Figure 2.
Calibrated sensor data for gripper status and wrist forces and torques during fluid coupling task with an experienced cperator. Shown are jaw opening and clamping force (a), X, Y, and Z, axis forces (b), and pitch, roll, and yaw torques (c). (data set: ag0.7) Forces in lb; torques in ft-lb.

the other data sets. Forces and torques change rapidly, and the force and torque recordings often appear to consist of a series of rectangular pulses at a repetition rate of about 0.2 - 0.5 Hz.

6.2.2. Discussion

Although there is tremendous variation among the recorded data, some interpretation of the force and torque record is possible from knowledge of the task. Performance of the task was complicated by difficulty of visual alignment, jams, and inaccurate manipulator control; and operators may have used differing strategies in performing the tasks. Thus, the features described below do not appear in all of the records, and they are intermixed with seemingly random activity. However, they appear in enough of the recordings to allow the construction of a schematic force torque history (figure 3) of the essential components of the task. The purolator fluid coupling task is of the twist and lock type similar to the common BNC electronic connector. Thus, in theory at least, the task of removing or inserting it requires only Z axis force (insertion/removal) and roll torque (lock/unlock). All other force and torque activity then is the result of misaligment, the resulting jamming of the mechanism, and attempts by the operator to eliminate this condition prior to actual task related activity.

Idealized Force Torque Behavior: Fluid Coupling Task

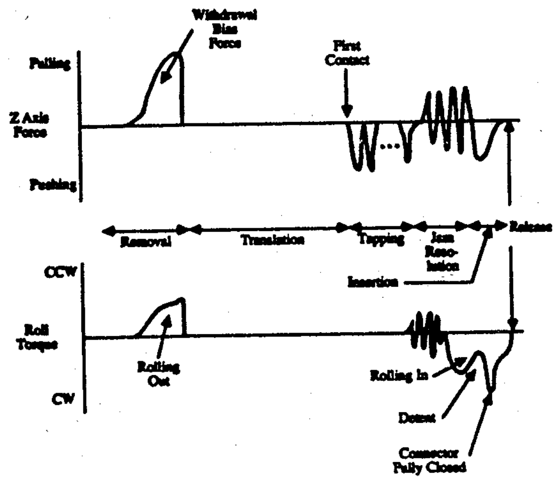
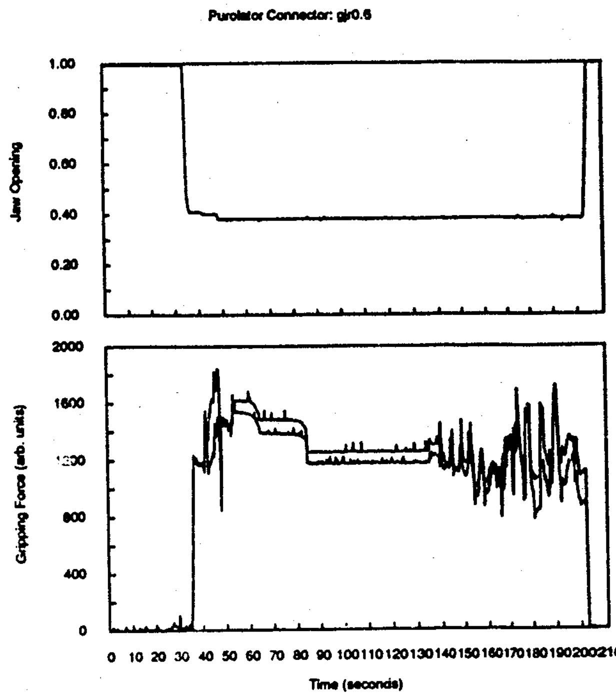
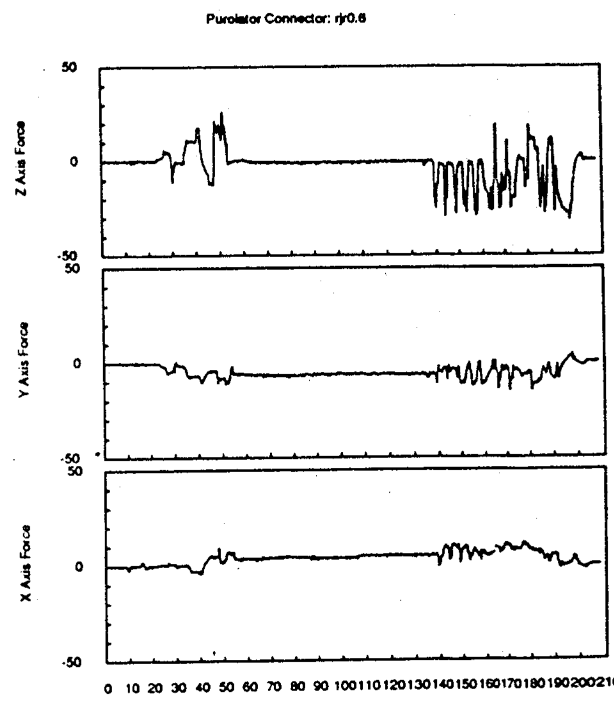


Figure 3.
Schematic force torque history for selected components of wrist force/torque for the Purolator connector fluid coupling task. Only Z axis force and roll torque are shown because they are the minimal set of force/torque components required to perform the task (see text).



(a)



(b)

During the translation phase, only gravitational forces are exerted on the wrist. Although most of the weight of the fluid coupling was counteracted by a tool balancer, the net gravitational force was still negative, and this is visible as a shift of about -5 lb on the Y axis force during translation. A smaller bias is visible in the X axis due to the fact that the wrist was rolled during translation (causing a gravitational component in the wrist-oriented X direction) and to the force of the trailing coiled hose. The large positive extent of Z axis force at the end of the removal phase shows the operator's strategy of applying a bias force in the direction of removal and manipulating the coupling until it popped out.

Torque traces can also be interpreted with knowledge of the task. For example, the roll torque is positive (i.e., in the direction required to open the connector) just prior to removal (biasing strategy) and negative (i.e., in the direction required to close the connector) just prior to completion of insertion. These directions are consistent with the function of the fluid coupling and were observed in most of the experimental data.

6.2.3. Typical naive subject

The selected inexperienced subject was an administrator with little previous experience on the system. The selected data set (figure 4abc) is one recorded after 10 practice runs. Task completion took more time (200 sec vs. about 170 seconds for the experienced operator).

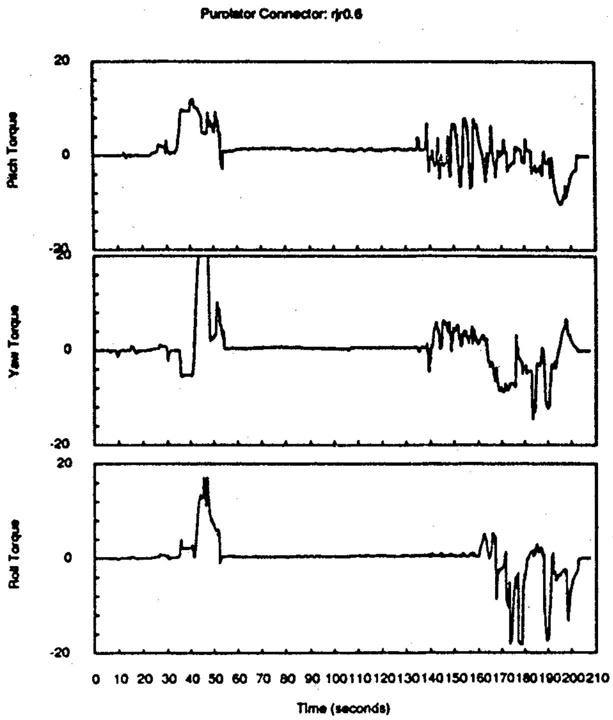


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Figure 4.
Force torque history for fluid coupling task with inexperienced operator. Jaw opening and clamping force (a); X, Y, and Z axis forces (b); and pitch, roll, and yaw torques (c). (data set: jr0.6)

6.2.4. Discussion

A distinguishing feature of this data set is the group of five pulses of negative Z axis force prior to insertion of the coupling. These pulses correspond to the observation by the test conductor that the operator was having difficulty aligning the connector with its socket and was repeatedly trying new locations and attempting to insert the connector. The strategy was thus to translate parallel to the task board (the X and Y directions), and then to attempt translation into the board (the Z direction). In the case of the illustrated data, this "tapping" strategy was tried 5 times in about 20 seconds (sampling rate of 0.25 Hz) before the alignment was correct and the locking operation was attempted (first deflection of roll torque).

The extremely high (over 20 ft-lb) value of yaw torque visible during the unlocking phase was a jam condition which had to be corrected before the fluid coupling could be removed, and the rollout-detent-lock feature can be seen in roll torque just before the end of the task.

6.3. Module Changeout (Box) Task

This task consisted of removing a light weight rectangular box (about 1 ft x 1 ft x 2 ft long) from a close fitting enclosure, moving it to a new position and orientation, and then moving it back and re-inserting it. Compared to the fluid coupling, this is an easier task in a more compliant environment (the box had significant compliance relative to the metal connector). The completion time for this task was relatively short.

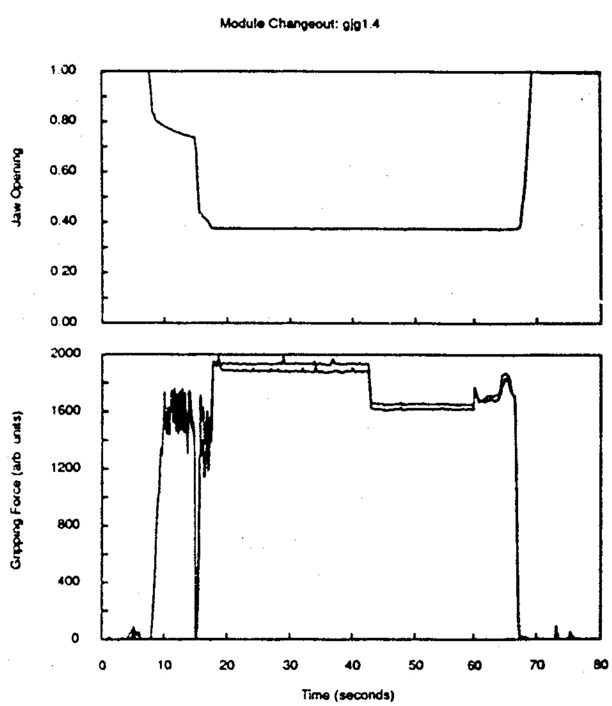
6.3.1. Forces and torques, etc

This data set (figure 5abc: experienced operator) is selected to show the interaction between the forces, torques, and gripping force, typical of these tasks. In the jaw opening trace, we can see that the gripper closed down in an irregular fashion over a period of about 10 seconds and that gripping force increased noisily during that interval. By about 15 seconds into the data set, the jaws have closed all the way down onto the handle (corresponding to about 40% of the full jaw opening), and the removal is accomplished in relatively short order (positive Z axis force, t = 15 - 20 seconds). Insertion is accomplished later (negative Z axis force, t = 65 sec), with negligible other forces.

Roll torque rises to about 20 ft-lb as the jaws are closing (t= 10-20 seconds) but falls to zero when the object is removed. Torques are moderate during insertion (t = 60 - 70 seconds) and fall to zero before the jaws are opened.

6.3.2. Discussion

The salient feature of this data set, the interaction between jaw closing, clamping force, and roll torque illustrates the strong coupling between axes in manipulating a free object in contact with a rigid non-moving environment. The coupling between jaw closing and roll torque arises from an initial misalignment in the roll axis between the claw and the box handle. As the jaws close, they create a roll torque, and the two points



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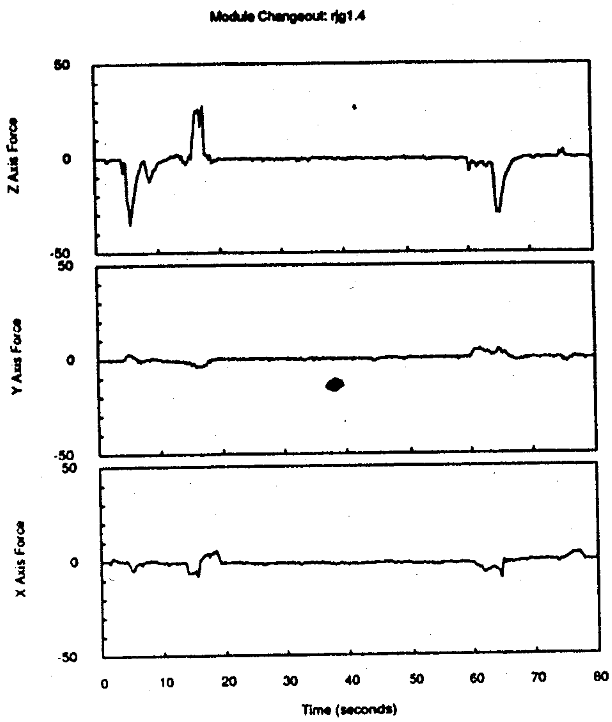

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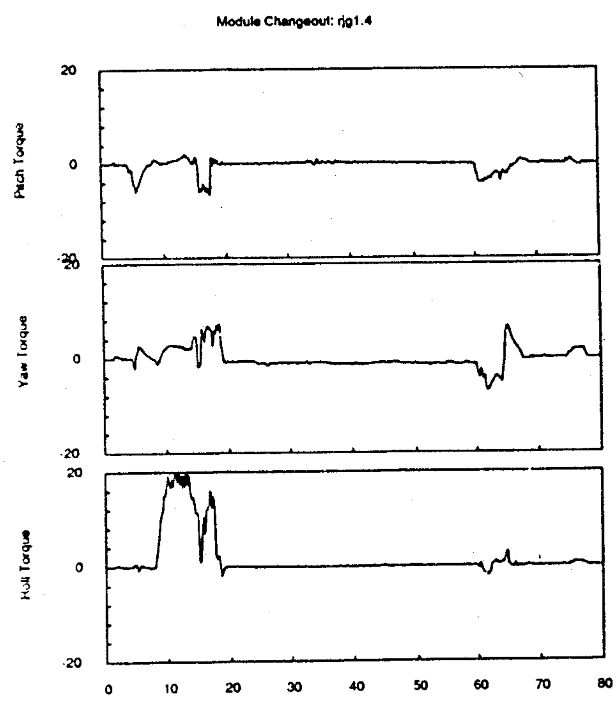

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Figure 5.
Force torque history for module changeout task (box) with experienced operator. (data set: jgl.4)

of contact slide along opposite sides of the box handle (which is complying to the roll torque). Surface roughness of the handle caused noise in the clamping force and to a lesser extent roll torque traces. Finally, perhaps due to a roll command, or perhaps due to a sudden shift in the handle position, grip force momentarily drops to zero and the jaws quickly move to the fully closed position.

6.4. Generic force/torque control task

6.4.1. Results

The results of the task board experiments give a picture of force and torque activity in performance of tasks that approximate anticipated space telerobotic tasks. A simpler set of experiments was undertaken to determine the operator's ability to control forces and torques in a single degree of freedom when this was the primary object of the task. In these experiments, the gripper was locked on a fixed handle, and the operator was asked to exert a specified force or torque level in a single axis. The specific task consisted of asking the operator to exert the force or torque for 30 seconds, to return to zero for 10 to 20 seconds, and then to re-apply the force/torque for 30 seconds. This task was studied only with the force torque display.

This task proved to be extremely difficult because the arm was not provided with any type of force control. As rate commands were given by the operator, the force or torque very rapidly increased to its maximum value. When it was possible, force control was accomplished by commanding a position at which arm compliance would set the desired force. Where this was not possible, oscillation often occurred.

Selected records from the generic force torque task data illustrate these phenomena (figure 6). In the first record (rbj2.1) the subject attempted to exert a specified Z axis force into the surface of the task board (-20 lb). The result is an oscillatory force signal indicating the instability of the arm and or operator in this control task. This oscillation is also present in the second example (rbj2.2), in which the 'target' was a Z axis force of -40 lb. The oscillation appears in at least two different modes: a low frequency mode at about 0.5 Hz (rbj2.1) and high frequency mode at about 1.4 Hz (rbj2.2).

6.4.2. Discussion

In the data presented here, the high frequency mode appears to arise from the arm control system. It is possible that the low frequency mode is due to human operator induced oscillation. Further experiments, in which additional relevant signals such as control input are recorded, are necessary to determine if this is the case and under which conditions operator induced oscillation can arise. The main result of this experiment, however, is the realization that a sophisticated display alone cannot be expected to significantly improve operator force control performance unless the manipulator control system supports some type of force control.

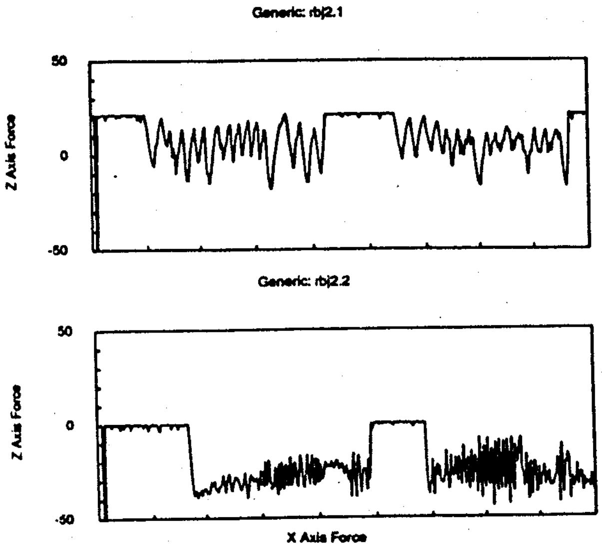

Figure 6.
Selected components from the generic force/torque task. In these records, the subject attempted to maintain constant force levels for periods of approximately 30 seconds. Pushing task: 20 lb in the Z axis, in the direction into the task board (a: data set rbj2.1); 40 lb along the negative Z axis (b: data set rbj2.2).

Cross coupling between axes is evident from these data. The axis most effected by Z axis force in both records is pitch torque. This arises naturally from the configuration of the arm when grasping a task board handle, because the wrist mounted actuator, joint 4 of the PFMA, is coupled to both Z axis force, and pitch torque.

6.5. Characterization of Task Performance: Reduced Data

Reduced data gives a single number characterizing the particular task performance. Sum of Squared forces and RMS force, are two such measures which integrate the magnitude of forces and torques. Since forces and torques are associated with jams, and excessive forces and torques could result in damage to equipment, lower values of these force / torque measures can be an indicator of 'better' task performance.

The performance measure used (RMS or Sum of Squared (SOS) forces/torques) must be carefully considered in light of the nature of the task. Since the task consists of two distinct periods of force/torque activity (removal and insertion), separated by a relatively quiet translation phase (figures 2,3,4), it is not appropriate to use these measures to characterize the whole run. For example, variations in the translation time would modify RMS or SOS measures in ways not related to the control of forces and torques by the operator. For this reason, RMS and SOS measures were computed for only the time period corresponding to a given sub-task. The reduced data reported here were computed during the insertion phase of the task. The time interval corresponding to the insertion phase was determined from the force/torque plots.

The two measures, RMS and SOS force/torque, are related to each other but differ in one significant respect. RMS force/torque differs from SOS force/torque because the RMS value has been divided by the number of samples in the selected time interval. This will tend to ignore the difference between trials taking a lot of time (jams) and trials with brief force/torque records (normal insertions). The SOS measure is not normalized in this way and thus reveals a measure of the total difficulty of the task.

6.5.1. RMS Forces

RMS force was plotted for 37 repetitions of the purolator fluid coupling task by several different operators (figure 7a). The results are broken down by experience level of the subject, and whether the task was performed with or without the force/torque display. Force levels are apparently uncorrelated for the naive subject.

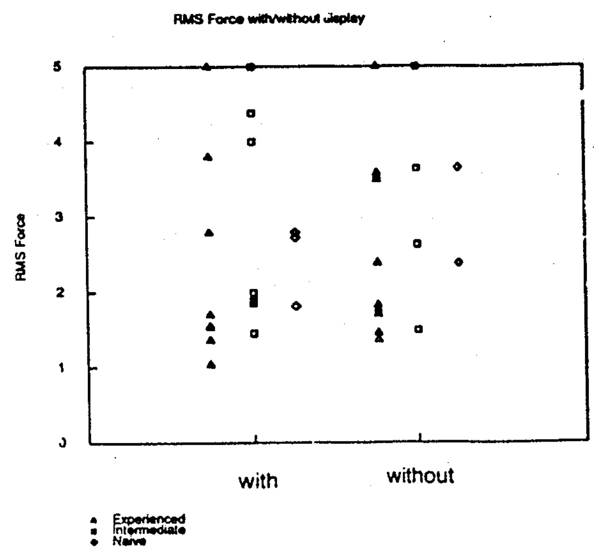

Figure 7a.
RMS force/torques for the insertion phase of the Purolator fluid coupling task.

6.5.2. Sum of Squared Forces

SOS force data were plotted for the same repetitions of the task (figure 7b). The overall pattern is similar to the RMS data.

6.5.3. Reduced Data: Discussion

The reduced data apparently show that the operator's ability to control forces is not significantly affected by the force/torque display. Although trends might prove significant with more data points, they would most likely be very small ones. Possible reasons for the absence of effect are that test subjects could not understand the display, or that test subjects could interpret the display, but could not perform corrective control actions.

The test subjects ability to interpret the display was not directly tested, but the

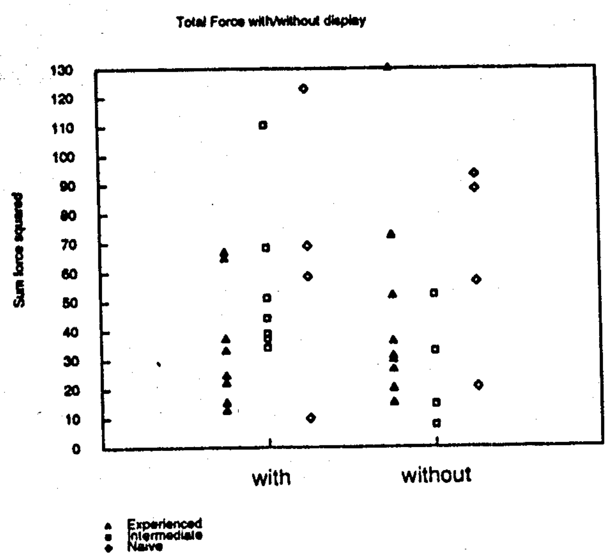

Figure 7b.
Sum of Squared force/torques for the insertion phase of the Purolator fluid coupling task.

display was explained to each subject, they were encouraged to ask questions, and they exerted forces and torques on the claw with their hands while observing the display. On the other hand, since the display was not transformed into task space coordinates, the information became more and more decoupled from the control actions as the hand deviated from the straight ahead position. In the case of this task, these deviations were small, but significant with respect to wrist roll.

The inability to control a perceived force was a more serious problem inherent in the test setup. The manipulator's control system supported only rate control of manipulator position. Because the environment consisted of metallic objects of high stiffness, small position changes could not be effectively used to control forces.

However, the lowest overall force levels were achieved by the most experienced operators. This was probably due to their proficiency in precisely positioning the manipulator to avoid jams. The highest force levels occur with the naive subjects, reflecting their difficulty with jams and alignment (the tapping strategy). For the intermediate subjects, force levels appear <u>lower</u> without the display. Although this may not be statistically significant, it is possible that attempting to use the display information was distracting to these subjects and resulted in poorer task performance.

6.6. Operators' Subjective Responses and Feedback

Although not systematically studied, comments and impressions of the subjects (often spontaneously offered) were recorded. The following is a list of some points expressed by individual subjects:

- Experienced operators found the display useful for resolving situations in which the fluid coupling was jammed.
- Operators had difficulty controlling forces and torques with the manipulator's available rate control (of position only) mode (see below).
- The Force Torque display needs on-screen labels or legends for each force torque component bar graph.
- The display should be resolved into the same coordinate system as the control.
- For the fluid coupling insertion task, high accuracy alignment information should be displayed rather than forces and torques.

7. RECOMMENDATIONS

Experienced operators found that the display of force-torque information was useful in various phases of telerobotic task performance. However, task level testing of the JPL-OMV Smart Hand has demonstrated little or no reduction in potentially damaging forces and torques due to the display of force/torque information to the operator. The probable reason for this is that although force-torque information was made available to and understood by the operators, they were no better able to <u>control</u> forces and torques because that control mode was not provided by the manipulator control system.

Experience with a more precisely controllable manipulator, the RMS simulator at Johnson Space Center, has demonstrated that a form of force control can be accomplished with small position commands (K. Corker, personal communication). The resulting force is a function of the stiffness of the environment and the manipulator. Improved control modes will be required to go beyond this ad hoc method if telemanipulation is to be extended into the domain of energetic interaction.

The conclusion to be drawn is that display devices, sensors, actuators, and control modes for teleoperation cannot be designed or fully evaluated in isolation. For optimum performance, the full teleoperation control loop, including the human operator, must be considered.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] Bejczy, A., B. Jau, "Servicing with Smart End Effector on OMV Manipulator," Proceedings, Satellite Services Workshop II, NASA Johnson Space Center, Nov. 6-8, 1985.

[2] Bejczy, A., E. Kan, R. Killion, "Integrated Multi-Sensory Control of Space Robot Hand," Proceedings, AIAA Guidance and Control Conference, Snowmass Colorado, Aug. 19-21, 1985.

[3] Shields, N., M.F. Fagg, "ProtoFlight Manipulator Assembly," Contract Final Report, NAS8-35320, Report No. H-84-01, Essex Corp., Huntsville, Alabama, April, 1984.

[4] Hannaford, B., "Plot2d, a charting and graphing program for the VAX," (JPL Internal Document, JPL Interoffice Memo 347-86-602), Jet Propulsion Laboratory, Pasadena, California, July 25, 1986.