Monocular TV vs Stereo TV for Solar Maximum Satellite Repair Subtasks

Daniel B. Diner

Abstract

Several operators performed two Solar Maximum Repair subtasks while viewing the workspace with either three monocular (non-stereo) black and white TV cameras or with one pair of stereo black and white TV cameras. For the monocular TV viewing, the three camera views were presented on three TV monitors, and a second operator controlled the pan, tilt and zoom lens power of two of the cameras. For the stereo TV viewing, neither pan, tilt, nor zoom adjustments were allowed, and no second operator was present. Operators were instructed to perform the subtasks as quickly as possible.

In all cases, operators completed the tasks more quickly with stereo TV viewing than with multiple monocular TV viewing. Operators reported the learning of the subtasks to be easier with stereo viewing, and reported the most difficult aspect of learning with monocular viewing to be learning which monitor to observe during the various phases of the subtasks.

End-effector force and torque feedback was applied to the hand controller, and force and torque data was collected during all experimental runs. However, for the sub-task examined in this paper, no clear relationship between the force/torque data and operator performance could be found.

1 Introduction

One of the more complex Extra Vehicular Activity (EVA) tasks performed in recent times in space was the Solar Maximum Satellite Repair (SMSR). In 1987, Central Research Laboratories Division (CRL) of Sargent Industries performed a Solar Max Repair Demonstration at Goddard Space Flight Center [1]. They used nuclear industry teleoperation capabilities to replace the Solar Max main electronics box. JPL has recently been funded to repeat the CRL demonstration with state-of-the-art teleoperation capabilities and thus show an increase in performance which promises to open new doors to teleoperation in space.

The task of opening, securing, closing and restoring the SMR thermal blanket was reported to be the most difficult task for the CRL demonstration. Thus we selected the first subtasks of the thermal blanket opening task for our preliminary experiments [2]. In order to ensure optimal operator performance, an optimal remote TV viewing system is desired.

This part describes the first of a series of experiments designed (1) to quantify operator performance under stereo TV vs multiple monocular TV viewing conditions, and (2) to investigate the relationship between end-effector force/torque data and operator performance. This first experiment tested two SMR subtasks, knife grasp-pickup, and horizontal cutting of the thermal blanket tape. Operators performed each of the two subtasks separately while viewing the workspace with either one stereo TV view or 3 monocular TV views.

2 Method

Operator performance was compared for the monocular camera viewing condition and the stereo viewing condition. Operator performance was measured by the time of completion of the subtask, and verbal reports

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of difficulty by the operator. In addition, the forces and torques generated during subtask completion were measured and analyzed. Force feedback was used in all experimental conditions.

The subtasks were conducted serially, i.e.; not randomly mixed. Thus, all operators were tested first for the knife grasp-pickup subtask, and next for the horizontal tape cutting subtask. One experimental run consisted of either only monocular or only stereo viewing conditions.

2.1 The Subtasks

The knife grasp-pickup subtask consisted of moving the robot end-effector from an initial rest position (20 cm to the left and 20 cm behind the knife grasp position) to the knife grasp position, closing the end-effector jaws, and lifting the knife off its Velcro rest-position holder. The closing of the jaws was found to be particularly slow, and so the operators often began the closing of the jaws "on the fly," that is, before reaching the knife grasp position.

The horizontal cut of the thermal blanket tape consisted of moving the end-effector (with the knife already grasped) from an initial rest position to cut the tape. The knife initial rest position was 30 cm to the right and 2 cm below the center of the horizontal cut location. The horizontal tape cut was 33 cm in length. The width of the space between the upper and lower thermal blankets varied between 1/4 cm and 1 cm (the thermal blanket mock-up edges were not straight due to the effect of the repeated experimental trials). The thermal blanket mock-ups were about 1 cm thick, leaving the front surface of the tape about 1 cm closer to the robot than the aluminum front surface of the SMR mock-up. Thus, the knife could penetrate the tape about 1 cm in depth before touching the hard SMR mock-up surface, where it often got stuck.

The knife could get stuck in three different ways during a typical unsuccessful cut attempt. The first way was to get imbedded in the thermal blanket mock-up. The second way was to dig into the hard front surface of the SMR mock-up. The third way was to get the knife stuck in a 1 mm wide crack between the main electronics box outer surface and the frame of the SMR mock-up. Thus a non-trivial amount of dexterity was required of the operators in performing this task.

2.2 The Multiple Monocular Camera Viewing System

The multi-camera frame installed in the ATOP laboratory was used to mount 3 monocular TV cameras: one behind the robots, one to the side of the robots, and one above the SMR work location. Each camera's initial view was centered upon a location on the SMR mock-up which allowed the operators to view different aspects of each subtask. The overall camera configuration was inspired by the suggestions of Ellis et al [3], to set the rear and side cameras perpendicular to each other and the top camera tilted downward at a 45 degree angle. Then, fine adjustments were made to the camera locations and pan and tilt angles until the operators could easily view all visual information relevant to performing the subtask.

For both subtasks, the locations of the cameras were identical, but the initial pan and tilt angles of the rear and side cameras were different. The top camera was never moved, neither during nor between subtasks.

2.2.1 The camera locations

In this paper, all locations will be defined with respect to the center of the horizontal cut of the thermal blanket tape. This point has been chosen for convenience, and any other point could have been chosen as well.

The top camera was located 18 cm to the left, 173 cm to the rear and 157 cm above the center of the horizontal cut of the thermal blanket tape. The rear camera was located 116 cm to the left, 248 cm to the rear and 15 cm above the center of the horizontal cut of the thermal blanket tape. The side camera was located 178 cm to the right, 52 cm to the rear and 10 cm above the center of the horizontal cut of the thermal blanket tape.

2.2.2 The camera viewing locations and angles

As mentioned above, the rear and side cameras' initial center-of-view positions were different for the two subtasks.

For the knife grasp-pickup subtask, the initial center-of-view locations (in the front surface plane of the SMR mockup) were as follows:

The top camera's center-of-view location was 1 cm below and 2 cm to the left of the center of the horizontal tape cut. Thus the top camera viewed the SMR mockup with an angle of 5 degrees clockwise yaw and 42 degrees downward tilt.

The side camera's initial center-of-view location was 5 cm below and 54 cm to the right of the center of the cut. Thus the side camera viewed the SMR mockup with an angle of -67 degrees clockwise yaw and 16 degrees downward tilt.

The rear camera's initial center-of-view position was 16 cm above and 20 cm to the right of the center of the horizontal tape cut. Thus the rear camera viewed the SMR mockup with an angle of 28 degrees clockwise yaw and less than 1 degree upward tilt.

For the horizontal cut of the thermal blanket tape, the initial center-of-view locations (in the front surface plane of the SMR mockup) were as follows:

The top camera's center-of-view location was the same as in the knife grasp-pickup task.

The side camera's initial center-of-view location was 2 cm below and 47 cm to the right of the center of the horizontal cut. Thus the side camera viewed the SMR mockup with an angle of -68 degrees clockwise yaw and 13 degrees downward tilt.

The rear camera's initial center-of-view location was 1 cm below and 14 cm to the left of the center of the horizontal cut. Thus the rear camera viewed the SMR mockup with an angle of 22 degrees clockwise yaw and 4 degrees downward tilt.

It is worth noting that the rear and side camera viewing axes were roughly perpendicular to each other, and that the top camera was tilted downward almost 45 degrees.

2.2.3 The monitors

Three monitors were used with the rear camera view on the left monitor, the top camera view on the center monitor and the side camera view on the right monitor. The central monitor is a Sony Triniton Super Fine Pitch 19" color TV monitor. The two side monitors are Conrac Model 5722N13 13" color TV monitors.

2.2.4 The second operator

As mentioned above, during the performance of a subtask, the rear and side cameras were panned, tilted, and zoomed in and out, in a manner previously established to be effective and comfortable for similar subtasks under multiple camera monocular viewing [4]. This required a second operator during the performance of the subtasks to control the cameras.

2.3 The Stereo Camera Viewing System

For stereo TV camera viewing only the central monitor was used. The two TV cameras were mounted on a precision-machined, stereo-camera mounting apparatus which could be manually adjusted to move both cameras symmetrically about the viewing axis [5]. The cameras were preset so that the relevant workspace was visible for each subtask. The stereo cameras' center-of-view location was 7 cm above and 8 cm to the right of the center of the horizontal cut for both subtasks. This is not the stereo camera convergence point, but is the point in the front surface plane of the SMR mockup directly behind the convergence point as measured from the center of the stereo camera rig. For both subtasks, the center of the stereo cameras was located 2 cm to the left, 207 cm to the rear and 41 cm above the center of the horizontal cut. Thus the stereo cameras viewed the SMR mockup with an angle of 3 degrees clockwise yaw and 9 degrees downward tilt. The zoom power of both cameras' lenses was set at 20 mm. The stereo images were presented via a Honeywell field-sequential PLZT Stereo Viewing System to the central monitor.

The stereo cameras were set at an intercamera distance of 20 cm, and converged to the rear of the workspace (50 cm behind the front surface of the SMR mock-up) so that all stereo images were perceived to be located behind the front surface of the monitor. The stereo cameras so configured give medium distortion and medium depth resolution [6]. High-distortion, high-resolution and low-distortion, low-resolution configurations were not tested. No pan, tilt, or zoom capability was allowed during the performance of the subtasks. Thus, no second operator was required or present for either subtask performed under the stereo viewing condition.

All the monocular and stereo cameras were Cohu 4810 Series black and white TV cameras with 754 usable pixels per horizontal line.

2.4 Training, Optimal Operator Performance and Data Collection

Due to severe programmatic time constraints, the training of some of the operators was not complete. Three of the operators had already been trained for 3 months on the subtasks with the multiple monocular cameras prior to this experiment. Operator 4 was not so well trained. In addition, all 4 operators were trained with the stereo viewing conditions for about 1 hour per workday for 2 to 3 weeks.

The operators were instructed to perform the subtasks as quickly as possible, and not to worry about minor equipment damage. They were also informed of two "optimal performance criteria" that were used during the data collection and are discussed below. Subtask performance completion times were measured by the experimenter (always the same one) with a stopwatch, and the operators were informed of the completion time of each experimental trial immediately. The operators were also coached by the experimenter as to how they could improve both their timing and their accuracy of performance. For example, an operator might be told, "You feathered the tip of the knife upwards for the final quarter of the cut, thus the tape was torn, and not cut, for the 3 cm at the end. This trial will not be counted as successful," or "You can save about a half second if you index the hand controller earlier," or "That was the fastest cut you have ever performed. Give me 9 more just like it," etc. It was believed that this type of feedback would decrease the time necessary for training. No quantifiable measures were made of this phenomenon, however, as that was not a goal of this research. That is, no control group was trained without the verbal coaching and feedback.

In order to compare operator capability under the two camera viewing systems, it was necessary to measure the optimal performance of the subtasks under each viewing system. Therefore, data were collected until the operators appeared to converge upon their optimal performance for the subtask and viewing condition at hand. Two "optimal performance criteria" were used to accept performance as converged to optimal. The first criterion was that the subtask was completed successfully 10 out of at most 16 trials; i.e., the knife was grasped properly in the end-effector gripper or that the tape was completely cut, and not partially cut or ripped apart. The unsuccessful trials were recorded but the times of completion of the unsuccessful trials were not included in the data analysis. The second criterion was that none of the 10 successful subtask completion times of each experimental run (one operator performing one subtask under one viewing condition) varied by more than 20% of the mean time for that run.

3 The Data

3.1 Subtask Performance Times

Table 1 shows the means and standard deviations of the subtask performance times for all operators and both subtasks under monocular and stereo camera viewing conditions. Operator 4 did not perform the tape cutting subtask.

A two-way analysis of variance of the data of Table 1 was performed with the independent variables of Cameras and Operator. The results are shown in Table 2.

Table 1
Mean Subtask Performance Times and Standard Deviations (in sec) for Multiple Monocular vs Single Stereo Camera Viewing Condition

A. Knife Grasp and Pickup		
Operator	Monocular Cameras	Stereo Cameras
1	3.72 ± 0.21	3.12 ± 0.18
2	3.80 ± 0.27	3.47 ± 0.13
3	3.96 ± 0.19	3.20 ± 0.35
4	4.93 ± 0.43	3.31 ± 0.32
B. Horizontal Tape Cut		
Operator	Monocular Cameras	Stereo Cameras
1	3.39 ± 0.11	2.83 ± 0.10
2	5.42 ± 0.23	4.68 ± 0.32
3	3.82 ± 0.17	3.49 ± 0.22

In both Tables 2A and 2B, the interaction effect of Cameras by Operator is significant. This means that the camera configuration (stereo vs monocular) is a significant factor in determining the subtask completion time, and further, that the effect of the camera configuration is different for the different operators. This can be seen in the data of Table 1. For example, in Table 1A, the use of the stereo camera viewing system in place of the multiple monocular camera viewing system reduced the subtask completion times by 16% for Operator 1, 9% for Operator 2, 20% for Operator 3 and 33% for Operator 4. This explains the high significance of the interaction effect in Table 2A. In Table 1B, the use of the stereo camera viewing system in place of the multiple monocular camera viewing system reduced the subtask completion times by 17% for Operator 1, 14% for Operator 2 and 9% For Operator 3. The differences between operators are not as great as in Table 1A, and thus the interaction effect is not as significant in Table 2B.

Table 2
F and p values from two-way analysis of variance.

A. Knife Grasp and Pickup		
Independent Variables	F	p
CAMERAS	178.96	<0.001
OPERATOR	23.78	<0.001
TWO-WAY INTERACTION	20.38	<0.001
B. Horizontal Tape Cut		
Independent Variables	F	p
CAMERAS	104.31	<0.001
OPERATOR	471.66	<0.001
TWO-WAY INTERACTION	4.97	<0.02

In Table 2, surprisingly high F values are found for the main effects of Cameras and Operator. This is particularly true for the main effect of Cameras in Table 2A and for both main effects in Table 2B. A careful explanation of what these values represent will explain these high F values.

In the two-way analysis of variance, the main effects are measured not to test the significance of factors on the data, but to explain the distribution of the variances in the data. To test the significance of factors on the data, a one-way analysis of variance is appropriate, but only if the two-way interaction effect is not significant [7]. The one-way analysis of variance will always yield a lower F value for the main effects than will the two-way analysis of variance because in the two-way analysis of variance, the variance of the main variables and the variance of the interaction is not included in the within groups variance. For example, the variance of the factor Operator and the Interaction variance are not included in the within groups variance when the F value of the factor Cameras is computed. The one-way analysis of variance does place these variances in the within groups variance, thus increasing the denominator and decreasing the F values.

In Table 3, the one-way analysis of variance has been computed for each of the factors Cameras and Operator for both subtask completion times. These F values are smaller than the F values in Table 2, yet two of them are still quite large; i.e., the F value for Cameras in Table 3A and the F value of Operator in Table 3B.

The explanation for these large F values lies in the small variances of the data. As noted above, the data were collected until the operators appeared to converge upon their optimal performance for the subtask and viewing condition at hand. Two criteria were used to accept performance as converged to optimal. The second criterion, requiring that the 10 successful subtask completion times of each experimental run did not vary by more than 20% of the mean time, assures that the within groups variance will be small.

Table 3
F and p values from one-way analysis of variance.

A. Knife Grasp and Pickup		
Independent Variable	F	p
CAMERAS	68.35	<0.001
OPERATOR	5.79	<0.005
B. Horizontal Tape Cut		
Independent Variable	F	p
CAMERAS	6.01	<0.05
OPERATOR	159.68	<0.001

The second criterion was found to be quite reasonable, for, in the final data, almost all of the completion times of each experimental run in fact did not vary by more than 10% of the mean time; i.e., by half the amount allowed by the second criterion. Thus the surprisingly large F values are explained by the surprising repeatability (small within groups variance) of the operators in performing the subtasks.

As mentioned above, if the interaction effect of the two-way analysis of variance is significant, there is no need to compute the one-way analysis of variance [7]. In this report, the one-way analysis of variance (Table 3) was computed only to help explain the high F values for the main effects of the two-way analysis of variance. It should be stressed that the only relevant F and p values in Tables 2 and 3 are the Interaction values of Table 2.

3.2 Subjective Operator Reports

All operators reported that they felt less training was necessary for the stereo viewing than for the monocular viewing, and that they learned to perform the subtasks with stereo viewing conditions more quickly. (Operator 3 assigned a "75% certainty" to this statement, while the other three operators assigned 100% certainty to this statement.) Three of the four operators reported that under the monocular viewing conditions, it was difficult to learn which monitor to view during the various phases of the subtasks, and this made learning more difficult for monocular viewing than for stereo viewing. Operator 3 stated that the tape cutting subtask was easier with the monocular viewing condition because the depth distortions of the stereo view required unnatural compensations. Operator 4 did not like the stereo viewing "goggles", and reported that stereo viewing is always uncomfortable for him.

All four operators expressed discomfort with such fast teleoperation, due to concerns about damaging the equipment. Operators 1, 2, and 3 expressed that an intermediate speed would be optimal, and Operator 4 expressed that he always "likes to go slowly" when teleoperating.

Operator 1 expressed that a zoom capability on the stereo viewing system would be desirable, and that the "discomfort was increased" by the need for the second operator under the monocular viewing conditions. Operator 1 also reported poor contrast under monocular viewing occasionally due to glare interference, probably due to the cameras being panned and tilted.

3.3 The Force/Torque Data

Figures 1 and 2 show force/torque data for Operators 3 and 1 respectively, both for the horizontal tape cutting subtask. The data are to be read as follows: Positive values on the force diagrams correspond to forces exerted by an object on the end effector when the operator is pushing the end effector upward (Z), left (Y), and forward (X). Accelerations in free space would be in the opposite direction, and usually are smaller. Positive values on the torque diagrams correspond to torques exerted by an object on the end effector when the operator is rotating the end effector to the left (yaw), downward (pitch) or clockwise (roll).

4 Results

4.1 The Probabilities

The two-way analysis of variance shows that subtask completion times are significantly smaller with single-monitor stereo TV viewing than with multiple-monitor monocular TV viewing. This is true for both subtasks. In addition, the two-way analysis of variance shows that the completion times of the different operators are affected differently by the different viewing systems.

4.2 Subjective Operator Reports

In general, the subjective operator reports agreed with the subtask completion time data. However, one exception is noteworthy. Operator 3 reported that the tape cutting subtask was easier with the monocular viewing. However, the subtask completion time for Operator 3 was shorter with the stereo viewing, thus seemingly contradicting the subjective report. The resolution to this apparent contradiction may be the following: although Operator 3 found it necessary to work harder in order to compensate for the stereo depth distortion, the advantage of the stereo depth information outweighed the extra effort needed, thus resulting in shorter subtask completion times with stereo viewing.

4.3 The Force/Torque Data Results

In order to perform the tape cutting task, it was necessary that the operator index the hand controller at least once. That is, the operator had to release the "dead man switch" on the hand controller, and move the hand controller without moving the robot, in order to increase the total range of motion over which the operator could control the robot. This was necessary, as the gain of the hand controller had to be limited to prevent instability in the force-feedback loop.

Operator manipulator strategy can be seen in the force/torque data. For example, in Figure 1, one can see the reduced accelerations corresponding to the indexing of the hand controller during the motion of the end

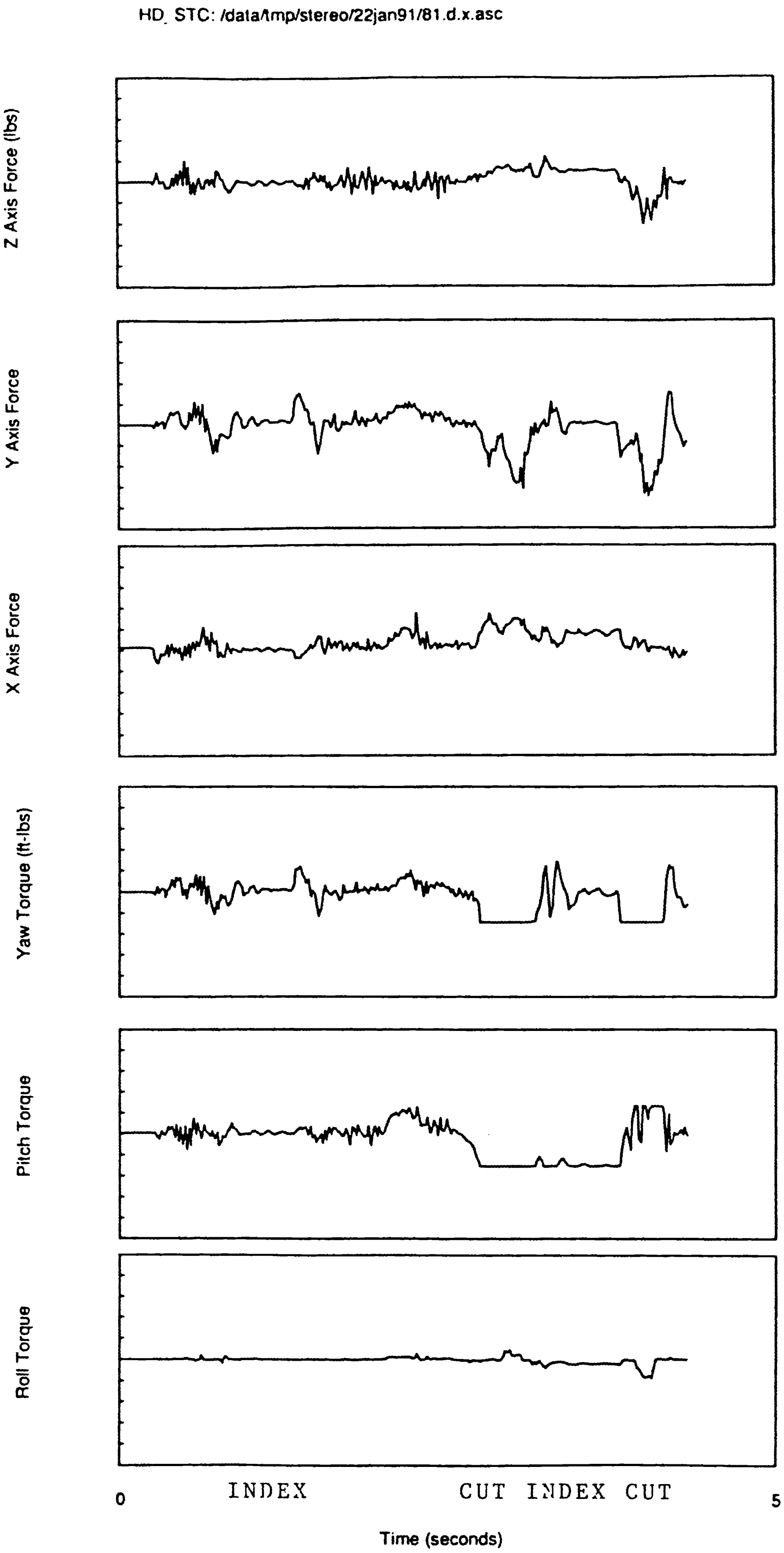
HD STC: /data/tmp/stereo/22jan91/81.d.x.asc
Z Axis Force (lbs)
Y Axis Force
X Axis Force
Yaw Torque (ft-lbs)
Pitch Torque
Roll Torque
0
INDEX
CUT INDEX CUT
5
Time (seconds)

FIGURE 1

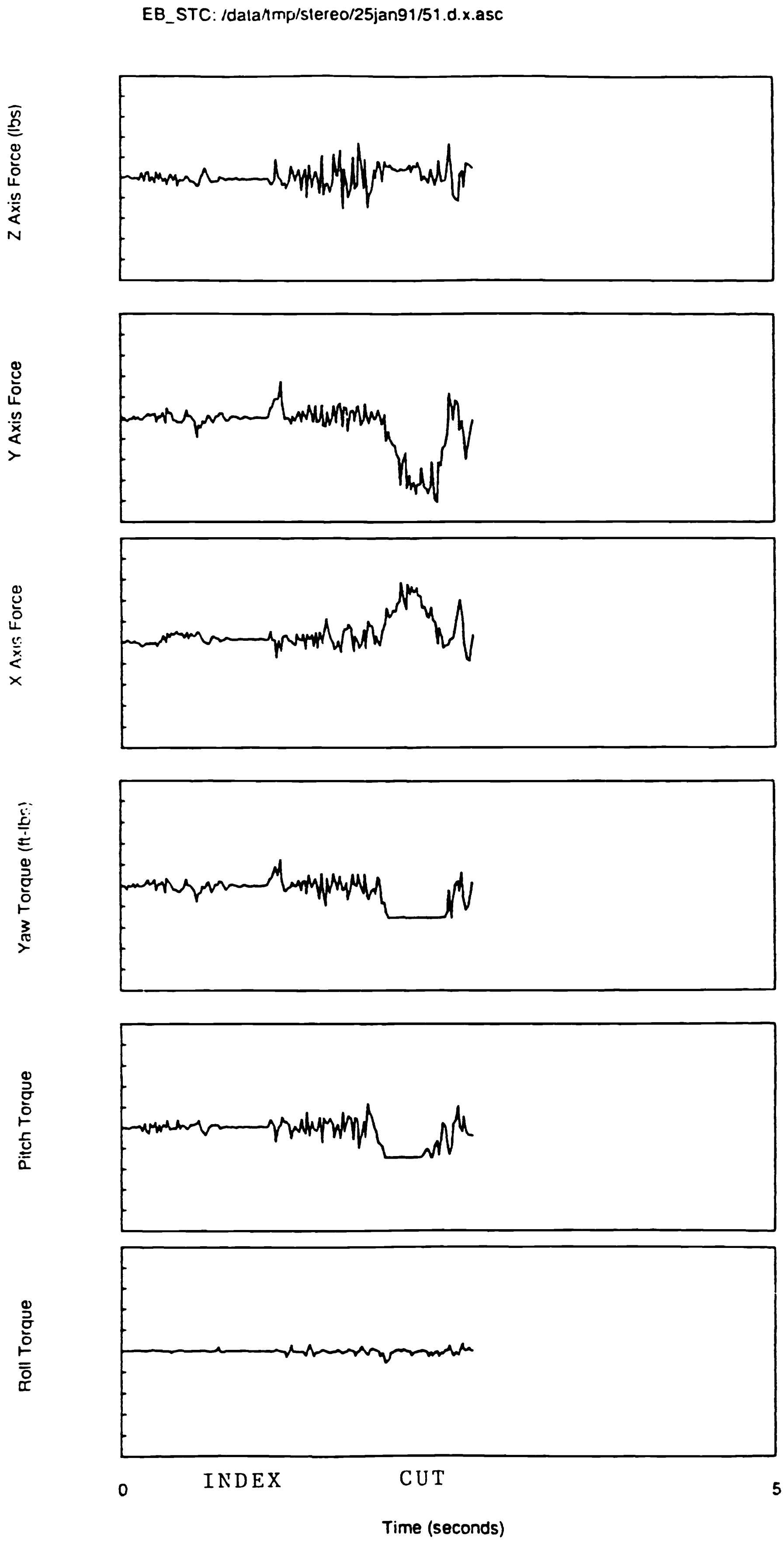
EB_STC: /data/tmp/stereo/25jan91/51.d.x.asc
Z Axis Force (lbs)
Y Axis Force
X Axis Force
Yaw Torque (ft-lbs)
Pitch Torque
Roll Torque
0
INDEX
CUT
5
Time (seconds)

FIGURE 2

effector towards the tape, and two cuts to the right separated by the second indexing of the hand controller. This strategy was followed by Operators 2 and 3.

In Figure 2, one can see a different strategy. Only one index and one cutting motion was made to the right. This was the strategy of Operator 1. Quite simply, Operator 1 learned to index the hand controller to an intermediate value when approaching the left end of the cut, so that he could cut the tape with one continuous cutting motion to the right. Operator 1 was clearly the fastest tape cutter, as Table 1B shows. This unique strategy of using an intermediate size index procedure to avoid the need for a second index procedure is only quantifiable in the force/torque data.

5 Discussion

The stereo camera TV viewing system tested here yielded smaller subtask performance times for both subtasks than the multiple monocular TV viewing system. The stereo camera system has several advantages, including the need for less equipment, the reduced workload on the operator (by not requiring the constant shifting of view to several monitors during subtask performance), and the need for only one and not two operators.

5.1 The Force/Torque Data

For many teleoperation tasks, one might design an experiment such that lower peak or average force and torque values would correspond to better operator performance. In this experiment, however, because the operators were instructed to perform the subtasks as quickly as possible, larger forces and torques could correspond to higher accelerations and therefore indicate better operator performance. Of course, any time a tool contacts or rubs against the SMR mockup, forces and torques will be generated, i.e., larger forces and torques can also correspond to sloppy work. Furthermore, operators may have used the contact forces to help guide the knife during the cutting of the tape, further confusing the issue, because the contact forces and torques would then correspond to improved performance. For these reasons, no clear relationship between operator performance levels and measured forces and torques could be found for the experiments described in this report.

However, the force and torque data have proven useful in quantifying operator strategies during the performances of these tasks. Future work will include a comprehensive study of the potential of using the force and torque data to quantify operator performance.

6 Conclusion

Several operators performed two Solar Maximum Repair subtasks while viewing the workspace with either three monocular TV cameras or with one pair of stereo TV cameras. For the monocular TV viewing, the three camera views were presented on three TV monitors, and a second operator controlled the pan, tilt and zoom lens power of two of the cameras, in a manner that was previously determined to be appropriate to the subtasks at hand. For the stereo TV viewing, neither pan, tilt, nor zoom adjustments were allowed, and no second operator was present. Operators were instructed to perform the subtasks as quickly as possible.

In all cases, operators completed the tasks more quickly with stereo TV viewing. Operators reported the learning of the subtasks to be easier with stereo viewing, and reported the most difficult aspect of learning with monocular viewing to be learning which monitor to observe during the various phases of the subtasks.

Force and torque feedback was used, and force and torque data were collected during all experimental runs. However, no clear relationship between the force/torque data and operator performance could be found, due to the nature of the experimental tasks.

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