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Evaluation of Force-torque Displays for Use with Space Station Telerobotic Activities

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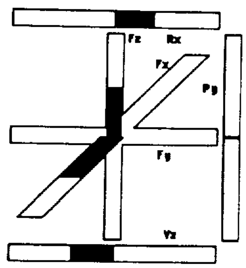
ABSTRACT

Recent experiments (NASA/MSD, 1991) which addressed Space Station remote manipulation tasks have found that tactile force feedback (reflecting forces and torques encountered at the end-effector through the manipulator hand controller) does not improve performance significantly. Subjective responses from astronaut and non-astronaut test subjects indicated that force information, provided visually, could be useful. No research exists which specifically investigates methods of presenting force-torque information visually. This experiment was designed to evaluate seven different visual force-torque displays which were found in an informal telephone survey. The displays were prototyped in the HyperCard programming environment. In a within-subjects experiment, fourteen subjects nullified forces and torques presented statically, using response buttons located at the bottom of the screen. Dependent measures included questionnaire data, errors, and. response time. Subjective data generally demonstrate that subjects rated variations of pseudo-perspective displays consistently better than bar graph and digital displays. Subjects commented that the bar graph and digital displays could be used, but were not compatible with using hand controllers. Quantitative data show similar trends to the subjective data, except that the bar graph and digital displays both provided good performance, perhaps due to the mapping of response buttons to display elements. Results indicate that for this set of displays, the pseudo-perspective displays generally represent a more intuitive format for presenting force-torque information.

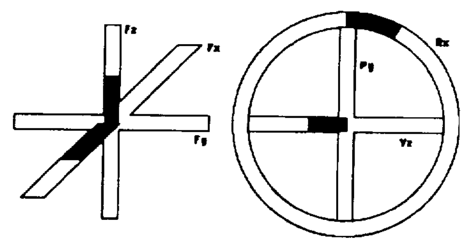
INTRODUCTION

Space Station *Freedom* will employ multiple telerobotic systems in its assembly and maintenance. These systems will have the capability to provide information back to the operator concerning the forces and torques encountered at the end effector (force feedback). Recent experiments at NASA's Johnson Space Center (JSC) (NASA/MSD, 1991) have found that for Space Station tasks, tactile force feedback provided through the manipulator hand controller (force reflection) does not improve performance significantly. However, qualitative responses from astronaut and experienced non-astronaut subjects indicate that force information can be useful. Force feedback can be provided via the visual modality (Hannaford, Wood, Guggisberg, McAffee, and Zak, 1989; Molino, Farbry, Langley, and Fisher, 1990) as well as the tactile modality (Hannaford, et al., 1989; Garcia, Chapel, and Spofford, 1990).

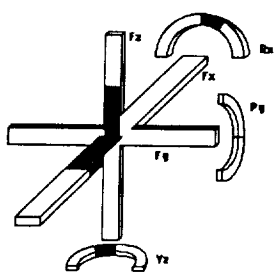
Bar graphs have been investigated as a means of presenting force-torque information visually (Bejczy & Paine, 1978; Bejczy & Dotson, 1982; Bejczy, Dotson, Brown, & Lewis, 1982; Molino, et al., 1990). Bejczy, et al., (1982b) found that the visual display aided the operators in performing a payload berthing task, especially in the terminal phase of berthing. Subjects in Molino, et al., (1990) commented that bar graphs were useful in situations in which the manipulator was bound up due to excessive contact forces. A pseudo-perspective graphic display of force-torque information (Figure 1, Display 1) was developed at the Jet Propulsion Laboratory (JPL). In this study, Corker, Bejczy and Rappaport (1986) found that the use of this display reduced the force



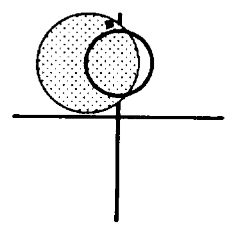
Display 1



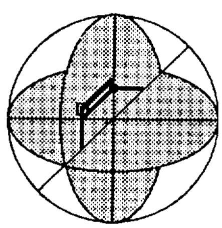
Display 2



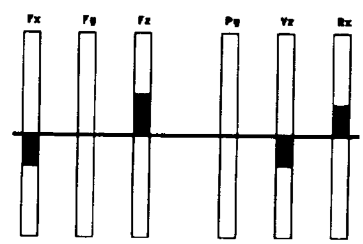
Display 3



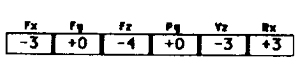
Display 4



Display 5



Display 6



Display 7

Figure 1. The seven displays investigated, each configured with equivalent forces in X, Z, Yaw, and Roll.

applied to payloads in a Remote Manipulator System (RMS) berthing task by 30-50% over the same task performed without the display. In a related study, Hannaford, et al., (1989) had one subject perform three different tasks using the JPL display and found that the visual display provided better performance than no feedback, but worse than tactile force feedback. In all of the visual force-feedback research previously conducted, none exists which directly investigates the best method of presenting force-torque information visually. Therefore, a need existed for an evaluation of this type.

An informal telephone survey was conducted to determine if there were displays that have been developed outside of JPL. Contacts were made with NASA personnel, universities, the nuclear industry, and aerospace contractors. Two alternative displays were found, one developed at Langley Research Center (Figure 1, Display 4) and a second (Figure 1, Display 5) developed within the Automation and Robotics Division at JSC. Two other displays (Figure 1, Displays 2 and 3) were developed by the Remote Operator Interaction Laboratory (ROIL) at JSC and are essentially variations of the JPL display. Display 6 is a generic bar graph display and Display 7 is a generic digital display included as a baseline.

This experiment was designed to evaluate the displays found in the survey in a controlled environment. The results may also be used to make modifications to the prototype displays and/or suggest guidelines for the display of force-torque information.

METHOD

Subjects/Experimental Design

Two groups of seven subjects participated. The first group consisted of volunteers from the Man Systems Division at JSC, all of whom had experience using a remote manipulator with 2 x 3 degree-of-freedom (DOF) hand controllers (separate controllers for rotation and translation, which are baselined for Space Station Freedom). The second group consisted of volunteers from JSC who had experience with the shuttle RMS simulator. While both groups had experience with remote manipulation, the Man Systems group was more experienced in human factors aspects of display design and the second group had more experience with operational concerns of using a remote manipulator.

Group (2), display (7), and number of axes with forces displayed (6) served as independent variables. Display and number of axes having force were within-subjects variables and group was a between subjects variable. The number of axes displaying force was controlled such that each display had four trials in which all six axes displayed forces, four trials with five axes of force, etc. Dependent measures included completion time, errors, and subjective data collected through questionnaires given after each display and at the completion of the experiment.

Apparatus

The experiment was conducted in the ROIL at JSC, using a Macintosh IIfx computer in the HyperCard programming environment. Both completion time and error data were collected by the program. The seven displays investigated are illustrated in Figure 1.

Procedure

The subject's task was to nullify the forces and torques presented by each display. This was accomplished via a set of buttons at the bottom of the screen which enabled the subject to manipulate the display in both positive and negative directions for each of the six axes (X, Y, Z, Pitch, Yaw, and Roll). If, for instance, a force was displayed in the positive X direction, the subject had to use the mouse and click the negative X button to eliminate the force. Each subject received 30 trials with each of the seven displays, with the order of display presentation being counterbalanced across subjects. The first six trials were practice trials which allowed subjects to become familiar with the operation of a display. After completion of 30 trials with a display, the subject filled out a questionnaire which addressed certain aspects of how well the display allowed the subject to detect the presence and monitor the changes of the displayed information, in addition to how well the display could be used with a set of 2 x 3 DOF hand controllers. After the subjects completed all seven displays, they were given a final questionnaire which allowed them to rate the displays after having seen each one. For both types of questionnaires, subjects were encouraged to rate the displays based on strictly the *concept* behind the displays (how intuitive they were for presenting force-torque information), and not how well the displays worked with the response buttons nor how smoothly the displays moved on the screen.

RESULTS

Analyses of variance (ANOVA) were performed on both the quantitative data and the mean ratings from each question of the questionnaires. In addition, Tukey's test of paired comparisons was run with each ANOVA to determine differences among displays and groups. Data from the two groups of subjects showed no significant differences between the groups, either for the final questionnaire or post-display questionnaire data. In addition, no significant differences between the groups were found for either errors or completion time. Therefore, the data for the two groups were pooled and analyzed as one group of fourteen subjects. Also, data from the post-display questionnaires were very similar to the data from the final questionnaire and will not be presented here.

Subjective Data

Final questionnaire data were collected using seven-point scales (1 corresponding to "completely acceptable", 7 corresponding to "completely unacceptable"). For question 1, which involved how acceptable the displays were for presenting forces in X, Y and Z, there was a significant main effect of display, $F(6,78)=11.78$, $p<.001$. The test of paired comparisons showed that Display 5 was rated significantly worse than all other displays, with Display 7 rating significantly worse than Display 3. Displays 1, 2, 3, 4, and 6 did not show any significant differences among each other. The main effect of display was also significant for question 2, $F(6,78)=13.36$, $p<.001$, which concerned the acceptability of the displays for presenting torques in Pitch, Yaw, and Roll. The test of paired comparisons showed the same differences as for question 1, except that Display 7 was rated significantly different than Display 2 instead of Display 3. Question 3 asked how compatible the displays were with using 2 x 3 DOF hand controllers. Again, a significant main effect of display was found, $F(6,78)=28.32$, $p<.001$. Displays 5, 6, and 7 all were found to rate significantly worse than Displays 1 through 4 in the test of paired comparison. Displays 5, 6, and 7 were not significantly different than each other. Finally, question 4, which involved how acceptable the displays were overall, demonstrated a significant main effect of display, $F(6,78)=13.71$, $p<.001$. The only difference in the test of paired comparisons showed Display 5 to be rated significantly worse than all other displays. Data from the final questionnaire are presented in Figure 2.

Quantitative Data

The main effect of display was significant for completion time ($F(6,108) = 13.22$, $p<.001$).

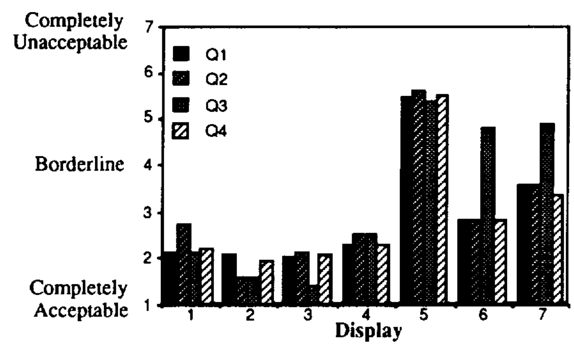


Figure 2. Mean ratings for each display by question.

The test of paired comparisons showed that Display 5 was significantly slower than every other display, while Display 4 was significantly slower than Displays 6, 7, and 2. Completion time data are shown in Figure 3.

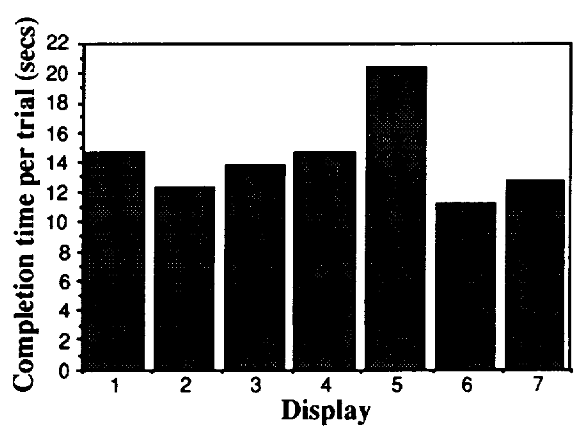


Figure 3. Mean completion times.

Three types of errors were recorded. Overshoot errors occurred when a subject, in eliminating a force or torque, went past zero and caused a force in the opposite direction. Reversal errors were scored when a subject applied more force instead of eliminating force. Confusion errors resulted when a subject attempted to zero-out a force that was already zero. For all three types of errors, the main effect of display was significant (overshoot errors, $F(6,108) = 7.69$, $p<.001$; reversal errors, $F(6,108) = 6.08$, $p<.001$; confusion errors, $F(6,108) = 5.34$, $p<.001$). Analysis of paired comparisons showed that Display 5 had significantly more overshoot errors than all other displays, and the remaining displays were not different than one another. For reversal errors, Display 5 had significantly more errors than all other displays, and Display 4 had significantly more errors than Display 7. Display 5 had significantly more confusion errors for all other displays as well, with Display 1 having significantly more errors than Display 6. Error data are shown in Figure 4.

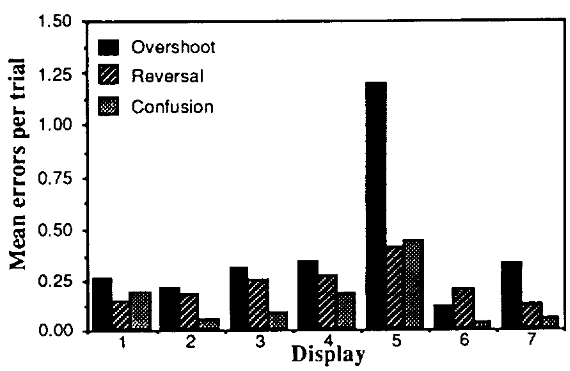


Figure 4. Mean overshoot, reversal, and confusion errors for each display.

DISCUSSION

Results from the final questionnaire can be broken down into two sections. Three of the four questions (1, 2 and 4) in the final questionnaire showed very similar relationships between the displays. For these questions, Displays 1 through 4 rated slightly better than Displays 6 and 7, with Display 5 being rated worst. However, for the question which asked about the compatibility of the displays with 2 x 3 DOF hand controllers (question 3), Displays 6 and 7 had similar ratings to Display 5, all of which were rated much worse than Displays 1 through 4. These poor ratings for Displays 6 and 7 were not unexpected, as there is no relationship between the elements of the displays and the spatial nature of force and torque information. Comments by subjects indicated that the method used by Display 5 of presenting torques, especially Roll, was not intuitive. In addition, when more than 3 forces or torques were displayed simultaneously, the intersecting lines created confusion as to which axes had forces. This situation caused several subjects to adopt a trial and error approach in identifying the displayed forces. A trial and error approach to relieving forces in an actual manipulation task, where highly expensive and delicate equipment is involved, is not a preferred strategy to adopt.

The results from the quantitative data differ from the subjective data mainly in the performance provided by Displays 6 and 7. Both displays had very few errors and generally faster completion times than all other displays. Their superior performance might be a result of an advantageous mapping of the display elements onto the response buttons. For both displays, the axes were presented from left to right on the screen as X, Y, Z, Pitch, Yaw, Roll, in the same order as the response buttons at the bottom of the screen. Due to the simplicity of the task, the number of errors committed was very low, generally less than one error per trial. It is interesting to note that overshoot errors followed the same pattern of results as the rest of the data, even though the occurrence of these errors was largely tied to how smoothly the displayed elements moved on the screen.

Display 5 consistently provided the poorest performance across all dependent measures. Display 4, was generally next-poorest to Display 5 with respect to the quantitative data. Display 4, however, was rated highly in both the post-display and final questionnaires. Subjects commented that this display was very intuitive in presenting torque information and was compatible with using 2x3 DOF hand controllers.

Displays 1, 2, and 3 had similar formats and produced similar ratings. Displays 2 and 3 however, generally rated slightly better due to their more intuitive methods of representing torques, as some subjects reported confusion between the Yaw and Roll axes on Display 1. Several subjects commented that the torque information on Display 3 mapped very well onto movement of a hand controller. For all three displays a large number of subjects commented that the location where the three force axes intersect needs some kind of graphic which would help in differentiating small forces.

CONCLUSIONS

Among these seven displays, Displays 1 through 4 seem to represent the most intuitive formats for presenting force-torque information. The results indicate that the "standard" or most widely known display, the JPL display (Display 1), may be improved upon significantly by simply modifying how torque information is presented. Display 4 represents a completely different method of presenting the information, and further testing in a more realistic task environment is needed to clarify the differences and make recommendations for display selection. The task utilized here did not involve a working manipulator or hand controllers, and the displays were essentially presented statically.

A second experiment is planned in which the top candidate displays identified in this study are incorporated into a working robotic system, with a 6 DOF manipulator and a set of 2 x 3 DOF hand controllers, to perform a task in which forces and torques must be observed and controlled. The selection of a display format may depend on other considerations such as screen space and computing power available. Both the use of color and auditory cues were not addressed by this study, as they may be added to any of these displays in a similar fashion.

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