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VARIABLE FORCE AND VISUAL FEEDBACK EFFECTS ON TELEOPERATOR MAN/MACHINE PERFORMANCE

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Abstract

An experimental study was conducted to determine the effects of various forms of visual and force feedback on human performance for several telemanipulation tasks. Experiments were conducted with varying frame rates and subtended visual angles, with and without force feedback.

1. Introduction

In Section two of this paper we describe our research objectives for conducting our experiments that focused on human/machine interaction for space teleoperation.

Section three contains descriptions of the experimental equipment. Our experimental design is discussed in Section four. Six test subjects used a master/slave manipulator during two experimental sessions. In one session the subjects performed the tasks with direct vision, with and without force feedback, and with the manipulator at three different distances from the task board yielding three subtended visual angles: 3.28, 1.64, and 1.09 degrees respectively. During the other session, the tasks were performed using a video monitor for visual feedback, with and without force feedback, and with three different frame rates (3, 5, and 30 frames/second) for the video transmission. The tasks were three peg-in-hole type tasks corresponding to 4, 5, and 6 bits/task according to Fitts' Index of Difficulty.

Experimental results for the video viewing and direct viewing environments are presented in Section five. The experimental data were analyzed through an analysis of variance. The video viewing results showed that frame rate, force feedback, task difficulty, and the interaction of frame rate and force feedback made significant differences in task times. For the direct viewing environment, subtended visual angle, force feedback, task difficulty, and the interaction of subtended visual angle and force feedback made significant differences in task times. Also in Section five are the results of comparing performance between the video and direct viewing environments. Comparable visual feedback to the human operator was provided by (a) the 1.64 subtended visual angle for direct viewing, and (b) thirty frames/second frame rate for video viewing. This allowed for an analysis between the direct and video viewing environments. While force feedback and task difficulty made significant differences in task times, the view itself (video vs. direct) did not.

Conclusions and suggestions are made in Section six based on the research results to help facilitate improved teleoperator performance for space operations.

Additional information on this experimental study can be found in [1].

2. Research Objectives

Performing a task directly with hands and eyes, unimpeded by physical distance, hardware, or artificial communication, has been observed experimentally to be quicker, easier, and usually more accurate than performing a task remotely using video and a remote manipulator device [2]. However, not all space tasks are well suited to be done manually by astronauts in extra-vehicular activity (EVA) due to the nature of the task, the risks and nature of the space environment, or the astronaut being constrained by his/her gloves or pressure suit. Thus there are safety, cost, and efficiency considerations that can make EVA procedures undesirable. Many researchers and engineers, faced with the necessity of remote viewing and handling, have sought to understand how human/machine interaction for the control of space teleoperators can be improved [3-5]. Nevertheless, knowing when to have manipulation tasks done by astronauts in EVA, remote manipulators controlled by humans, or autonomous robots is an important current issue.

The human operator's performance in telemanipulation can surely be improved by providing the operator with appropriate and adequate feedback. Teleoperation will not eliminate or drastically alter the need for humans in space, but it will alter the roles that humans fulfill in space and should improve human productivity there. The use of remote manipulators should also free up valuable crew time to be spent on other space operations and experiments.

The elements of a remote viewing and manipulation system include a video camera, a telecommunication channel, a video display, human eyes, human arms and hands, a master arm, a slave or robot arm, and the task operation itself (such as putting a peg into a hole). These elements have not only desirable but also undesirable properties. They tend to add undesirable forces, displacements, time, illumination, and contrast to the remote environment that would not be there in the manual situation. They can be perceived as "filters" that prevent information from reaching the human operator, and thus retard performance [2]. In the experiments presented in this paper the effects of various degrees of some of these "filters" were investigated including:

* Force feedback and its effects on motor capabilities.
* Video frame rate, and its effects at different values on performance.
* Subtended visual angle and its effects on task performance for manipulation with direct viewing.
* Task difficulty and its effects on the cognitive and motor capabilities of human operators.
* The use of a video monitor versus the use of direct vision for remote manipulation.
* The interactions of two or more of the above variables with each other and the corresponding effects on performance.

These "filters" and their effects need to be identified and quantified to provide information to facilitate efficient teleoperation in space. Experimental findings, quantified and analyzed through statistical methods, should prove helpful to researchers and policy makers alike. The results could be implemented over a variety of space applications including:

* space shuttle remote manipulator system [6]
* control of an orbital maneuvering vehicle with a robotic front end [7]
* telerobotic servicer on the space station
* a number of planetary and lunar missions such as a Mars sample return mission or lunar exploratory operations [8-9].

The major goal of the experiments presented here was to provide information to help technologists better understand what the capabilities of humans are when interfacing with space telemanipulators under various sensory feedback conditions.

3. Experimental Equipment

E2 Manipulator System

The E2 master-slave manipulator had the capability of operating with direct electronic coupling control both bilaterally with force feedback, and unilaterally without force feedback coming from the slave back to the master arm. Our E2 was right handed, as were all of the test subjects used in the experiments. Both master and slave arms had seven degrees of freedom including end effector gripping, were geometrically similar, and were kinematically isomorphic to the operator's arm and hand. The manipulator degrees of freedom are shown in figure 1. The E2 had seven degrees of freedom: three (x, y, and z direction) for arm translation, one for arm rotation (azimuth), one for gripper elevation, one for gripper twist, and one for the grasping motion of the gripper jaw. Tracking time delays were considered negligible during the experiments due to the manipulator's quick and accurate response to the operator's input motions [10].

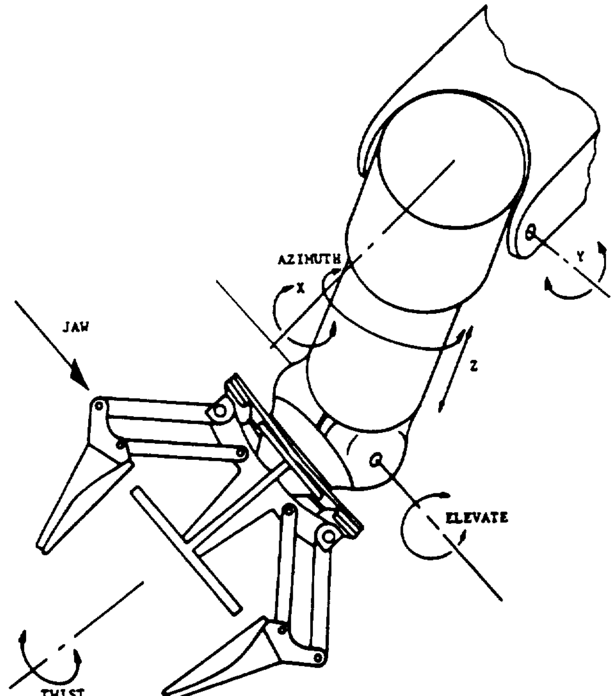

Figure 1 - E2 manipulator degrees of freedom. Source: [10]

Video System

Central to altering the video environment was the capability of varying the frame rate. This was accomplished through the use of the AT & T Truevision Advanced Raster Graphics Adapter (TARGA 16) board and a computer program. The resolution selected for the experiments was 512 X 256 pixels in order to have non-interlaced video input or output. TARGA captures images in real time:1/60th of a second per field or 1/30th per frame. Once a frame rate was selected, the TARGA board would capture a frame at the rate necessary to provide the requested frame rate. A color monitor provided the visual feedback to the test subjects.

Task Board

The task board consisted of four slots. Each slot was made with two side boards and a center board that formed a back. Figure 2 displays the task board dimensions. The two end slots were 3.75 inches wide and the middle slots were 3.25 and 3 inches wide respectively. The block used in the experiments was 2.75 inches wide, providing task tolerances from left to right of one inch, one-half inch, one-quarter inch, and one-inch. The redundancy of the one inch tolerance on the outer slots allowed the alternating of right and left motion. The centers of each of the four slots were eight inches apart. Mounted on the lower portion of each center block were limit switches that controlled the clock to record the task times.

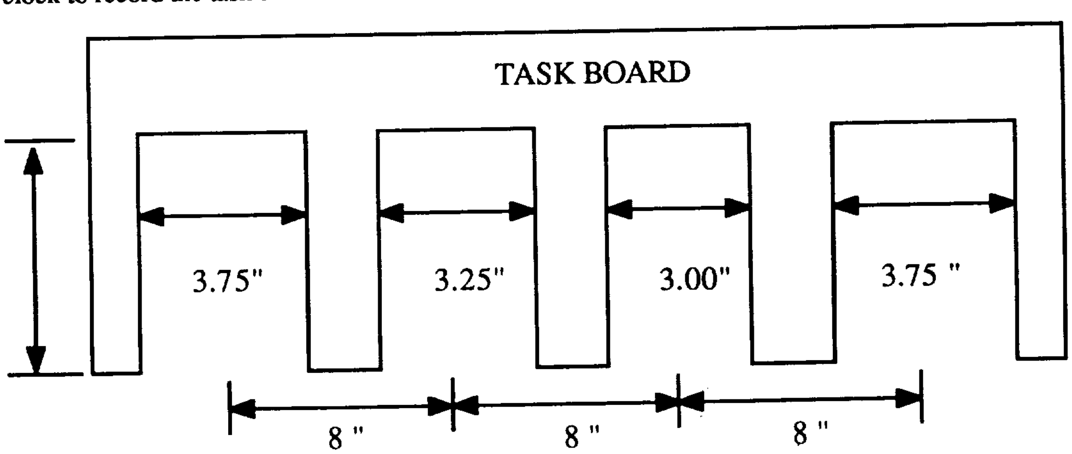

Figure 2 - Task Board Layout

4. Experimental Design

Tasks

The tasks consisted of moving the block of wood on the task board with the manipulator arm. Thus the distance moved (eight inches) versus the tolerance of fit (1,.5,.25 inches) provided multiples of 2 for easy use of Fitts' law [11] which applies the formula: Index of Difficulty (Id) in bits per task equaled $\log_2(2A/B)$, where A equaled the distance moved and B equaled the tolerance of fit. Fitts' law produced indices of difficulty of 4, 5, and 6 bits per task respectively.

Video Viewing Experiments

Since communication channels for teleoperation in space are often constrained by limited bandwidth for information transmission, decreasing the amount of information that needs to be transmitted can save time and money. Decreasing frame rate is one way to decrease the amount of information that is transmitted, and this section of the experiment was designed to measure the effects of varying frame rate on operator performance. The goal was to gain information on acceptable frame rates for controlling a remote teleoperator under different force feedback and task difficulty conditions.

The direct view of the task board was cut-off from the subject and the video monitor was used with three different frame rates: three frames per second (fps), five fps, and thirty fps, with and without force feedback, for a total of six experimental conditions. Thirty frames per second provided satisfactory image fusion, i.e. output that appeared as steady motion. Five fps and three fps were selected based on previous experiments and preliminary experimentation. Ranadive [12] found that a threshold frame rate existed at three fps beyond which task performance was virtually impossible. He also discovered that frame rates below 5.6 fps considerably degraded performance and increased variability. Preliminary experimentation confirmed these trends. After trying many frame rates, 30, 5, and 3 fps were chosen since they appeared to represent breaks in the performance curve.

Direct Viewing Experiments

The tasks were also performed with the subjects using direct vision for visual feedback, with and without force feedback. The master manipulator was placed at three different viewing distances from the task board: four, eight, and twelve feet. Each distance from the task board in the direct viewing experiments had an associated subtended visual angle. The formula: subtended visual angle = (57.3) (60) L/D degrees, gives a measure for subtended visual angle where L = the size of the object measured perpendicular to the line of sight, and D = the distance from the front of the eye to the object [13]. In this case L = 2.75 inches and D varied between 4 feet (48 inches), 8 feet (96 inches), and 12 feet (144 inches), yielding subtended visual angles of 3.28 degrees, 1.64 degrees, and 1.09 degrees respectively. This allowed analysis of the effects of varying subtended visual angles on task times.

Direct Viewing at 8 feet and Video Viewing at 30 fps

The eight foot distance yielded the same subtended visual angle as the experiments that were performed with the video monitor (1.64 degrees). This allowed for a comparison of the 1.64 degrees direct viewing data with the 30 fps video data since 30 fps appeared to the eye as a steady motion. Thus 1.64 degrees direct data and 30 fps video data each had subtended visual angles and frame rates that appeared equal to the human operator. Some of the major differences were stereo vision with direct viewing, the ability to move one's head to change the viewing line of sight with direct viewing, and the different environments surrounding the task board for each view. It was the effects on performance of the stereo vision and other differences in the views that were of interest in this section of the experimental design.

Experimental Procedures

Six MIT graduate students were used as test subjects. Each subject attended a one and a half to two hour training session a few days prior to performing the final experimental runs. The subjects were made familiar with the experimental design and procedures and became acquainted with the E2 manipulator system. They performed each task condition and repeated the tasks until they said they were familiar and felt comfortable with the manipulator and the manipulation environment. Then they performed the tasks for time just as they would in the actual experiments. When their performance times met minimum training levels and the learning effects subsided, the subjects were then trained on the next experimental condition.

Subjects then underwent two separate experimental sessions: one using the video monitor and the other for performing the tasks with direct vision. A balanced latin square was used so that each experimental condition preceded and followed every other condition an equal number of times to counterbalance the effects of fatigue and learning on the experimental results.

The video portion consisted of three frame rates, two forms of force feedback, and three different tolerances which corresponded to three different indices of difficulty for a 3x2x3 design. The direct vision experiments included three visual angles, and the previously stated feedback and tolerance/difficulty parameters for a 3x2x3 design. Each task was performed five times going to the right and five times going to the left for 5x2 = 10 tasks per condition. Six subjects were used so the video experiments had a total of 3x2x3x5x2x6 = 1080 number of data points, and the direct vision experiments also yielded a total of 3x2x3x5x2x6 = 1080 number of data points.

5. Experimental Results

The experimental data was analyzed through an analysis of variance (ANOVA) with a 95 percent confidence level as described in [14-15], and Newman-Keuls post-hoc testing as outlined in [16]. The results of the statistical analysis are illustrated in tables 1 and 2 and figures 3 to 8.

Table 1 - ANOVA results for variables and interactions with statistical significance during video viewing performance

SOURCE	Degrees of Freedom	F-VALUE	P-VALUE
Frame rate	2, 10	73.1	0.0001
Force feedback	1, 5	167	0.0001
Task difficulty	2, 10	15.3	0.0009
Interaction of frame rate & force feedback	2, 10	8.99	0.0058

Table 2 - ANOVA results for variables and interactions with statistical significance during direct viewing performance

SOURCE	Degrees of Freedom	F-VALUE	P-VALUE
Subtended visual angle	2, 10	57.8	0.0001
Force feedback	1, 5	49.5	0.0009
Task difficulty	2, 10	27.3	0.0001
Interaction of subt. vis. ang. & force feedbk	2, 10	6.91	0.013

Effects of Force Feedback

As displayed in tables 1 and 2, force feedback made a significant difference in performance. For video performance, force feedback was significantly better than no force feedback. With force feedback the average task time for all frame rates combined was 2.98 seconds and the absence of force feedback produced a combined average task time of 5.29 seconds.

Even when viewing was direct (no video), force feedback made a significant improvement in the mean task times. The presence of force feedback yielded a total mean task time of 1.71 seconds and without force feedback the total mean task time was 2.80 seconds.

Effects of Task Difficulty

For the video viewing experiments, task difficulty made a significant difference as shown in table 1. The Newman-Keuls analysis determined that only the quarter inch tolerance or the most difficult task (Id=6 bits) had significantly different mean task times from the other two tasks. The one inch tolerance task with Id=4 and the half inch tolerance task with Id=5 were not significantly different from each other. For Id=4 the mean task time was 3.55 seconds, for Id=5 the mean task time was 3.95 seconds, and for Id=6 mean task time was 4.90 seconds.

These relationships are more clearly represented in figure 3. The mean task time values are plotted for the three different indices of difficulty. The error bars represent the standard error for each mean. A linear regression yielded y=0.758+ 0.675x. An exponential fit was also done, yielding a relationship of time (y) to index of difficulty (x) of y=1.83*10^(0.07x). The pattern of the data points and the results of the Newman-Keuls post-hoc test suggest that the exponential plot described the behavior or trends of the data better than the linear plot. These were different from the linear results that Fitts [11] obtained but were similar to the results of Hill [17-18].

Although these results are based on only three data points, each data point is the mean of three hundred and sixty data observations. Further, the plots are only meant to indicate general trends in performance. Therefore it is with some confidence that these results are presented.

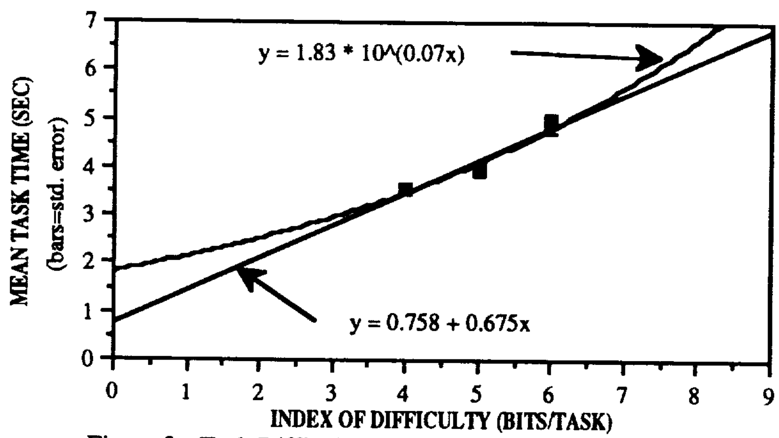

Figure 3 - Task Difficulty Effects on Video Viewing Performance

Table 2 displays that task difficulty also made a significant difference in performance for the direct viewing experiments. Post-hoc testing revealed that the easier tasks with Id's equal to 4 and 5 did not produce significantly different means. However, the most difficult task (Id=6) was found to yield task means that were significantly different from the other two. The mean task time for Id=4 was 1.89 seconds, for Id=5 it was 2.15 seconds, and for Id=6 it was 2.74 seconds. Figure 4 graphically displays the effects of task difficulty on direct viewing performance. Both a linear fit, y=0.138+0.424x, and an exponential fit, y=0.882*10^(0.081x), were performed. As was found with the video viewing results, the increases in mean task time displayed more of an exponential tendency than a linear one.

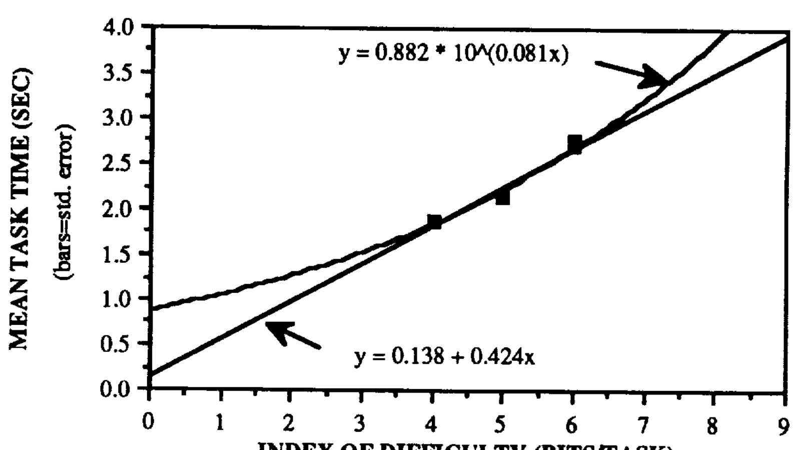

Figure 4 - Task Difficulty Effects on Direct Viewing Performance

Effects of Frame Rate

Frame rate made a significant difference in performance (table 1). The Newman-Keuls post-hoc test showed that all three frame rates were significantly different. Mean task time with a frame rate of three frames per second (fps) was 5.36 seconds, for five fps it was 4.48 seconds, and for 30 fps it was 2.56 seconds. These results are shown graphically in figure 5.

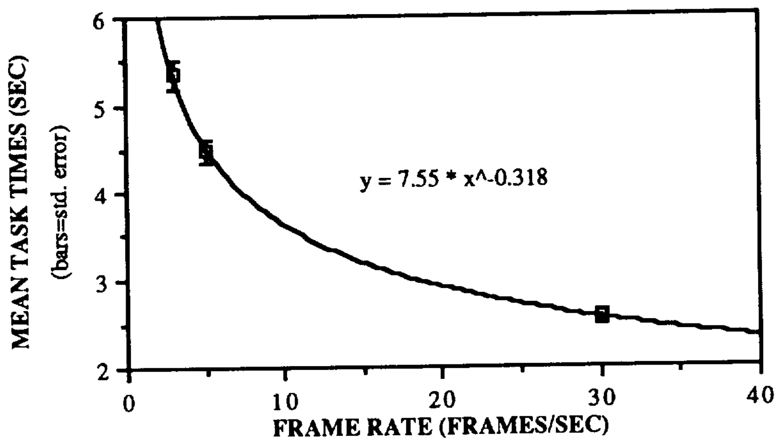

Figure 5 - Frame Rate Effects on Video Viewing Performance

Interaction Effects of Frame Rate with Force Feedback

The interaction of frame rate and force feedback was also noticed to make a significant difference in performance times (table 1). Post-hoc testing results showed that three frames per second (fps) with force feedback, five fps with force feedback, and thirty fps without force feedback were found to produce mean task times that were not significantly different from each other. Three fps without force feedback and five fps without force feedback were not significantly different from each other. Thirty fps with force feedback was significantly different from all other conditions. These results are graphed in figure 6.

While at each frame rate, force feedback made a significant improvement in performance times, force feedback yielded a larger performance improvement at lower frame rates than at higher frame rates. Even at 3 fps, force feedback provided such a large improvement in performance that the mean task time was not significantly different from 30 fps without force feedback.

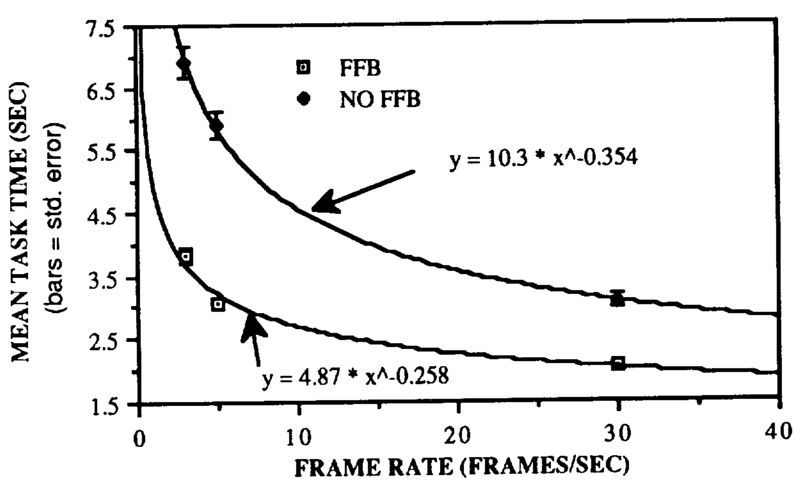

Figure 6 - Interaction of Frame Rate and Force Feedback

Effects of Subtended Visual Angle

Subtended visual angle did cause significant differences in mean task times (table 2). The Newman-Keuls post-hoc analysis determined that the three subtended visual angles produced task time means that were significantly different from each other. The mean task time for a subtended visual angle of 3.28 degrees was 1.92 seconds, for 1.64 degrees the mean task time was 2.27 seconds, for 1.09 degrees the mean task time was 2.59 seconds. These results are displayed in figure 7.

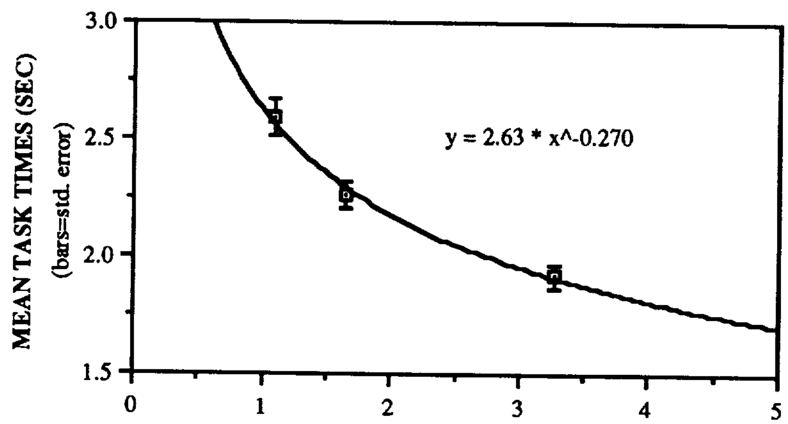

Figure 7 - Subtended Visual Angle Effects on Direct Viewing Performance

Interaction of Subtended Visual Angle with Force Feedback

The interaction of subtended visual angle with force feedback was found to make a significant difference in performance times (table 2). The Newman-Keuls post-hoc tests revealed that at all three subtended visual angles, force feedback versus no force feedback made a significant difference.

While operating with force feedback, decreasing the subtended visual angle did not significantly increase task times. Further, force feedback was able to improve performance at the smallest subtended visual angle by a margin large enough to make the task times not significantly different from those observed for the largest subtended visual angle without force feedback. Performing tasks without force feedback, and at a 3.28 degree subtended visual angle was not significantly different from that at 1.64 degrees without force feedback. However, performance at 1.09 degrees without force feedback was significantly different from that for the other two subtended visual angles without force feedback. These results are displayed in figure 8.

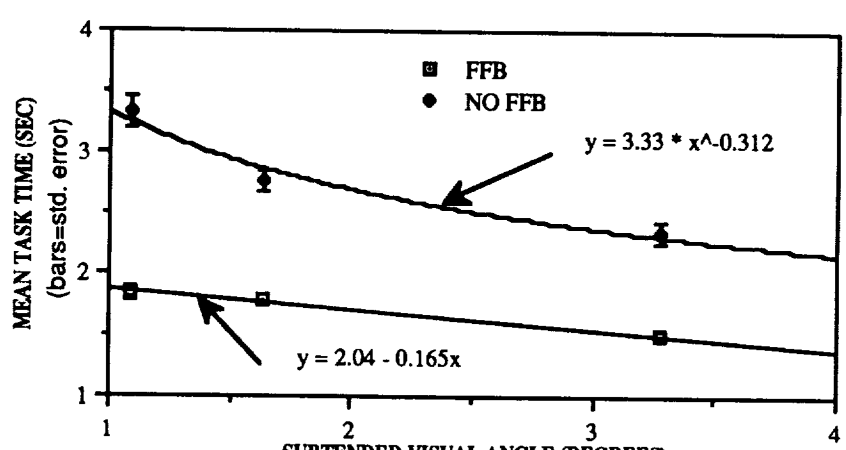

Figure 8 - Interaction of Subtended Visual Angle with Force Feedback

Effects of View (Video Viewing at 30 fps vs. Direct Viewing at 1.64 degrees)

When frame rate and subtended visual angle were similar, video and direct viewing mean task times were not found to be significantly different. This indicated that for these experiments whether the view was direct or video by itself did not make a difference and that the primary visual variables affecting performance were subtended visual angle and frame rate.

6. Conclusions and Recommendations

When using a remote manipulator system without force feedback, like the space shuttle remote manipulator system (RMS), and with direct vision, a relatively large subtended visual angle should be provided to the operator if possible. The experimental results suggested that in direct viewing telemanupulation, an adequate subtended visual angle could compensate for performance degradations that were due to the operator being at large distances from the task board. A larger subtended visual angle could be yielded by providing a larger target to increase the size of the image on the operator's retina thus increasing the subtended visual angle. Additionally, since force feedback would not be present, one would also expect that performance will be degraded more at smaller angles than it would be if force feedback were present.

The experiments indicated that frame rate and subtended visual angle were the visual feedback variables that affected performance significantly in the experiments, not whether direct or video viewing was implemented. Some previous studies (performed without a transmission time delay) concluded that position and force feedback are reconstructible to a large degree in teleoperation, but recreating the visual image as feedback to the operator was more challenging due to the loss of information (such as stereoscopic vision) when viewing a television monitor [19]. Our results suggested that there was not as a significant decrease in performance due to the loss of information when going from direct viewing to video viewing as might be expected. This leads one to conclude that if a manipulator without force feedback were being used (such as the RMS), and direct vision yielded a small subtended visual angle, it would be wise to use video transmission to provide a larger subtended visual angle. Although the video monitor may not provide stereoscopic vision, performance would probably be improved with the larger subtended visual angle. Thus if a choice is given between direct viewing with a small subtended visual angle against video viewing with a high frame rate and larger subtended visual angle, video viewing could be the wiser choice.

However, there may be other explanations for view not having a significant effect on mean task time. For example, the effects of stereo vision could be greater at shorter distances than at longer distances. Therefore it is possible that the eight foot distance was too great to utilize the full advantages of stereo vision. This is a topic for future research. Nevertheless the results found in these experiments suggest that the view itself did not have a significant effect on mean task times.

If teleoperation were to be controlled from a ground control station or a space station workstation with a video monitor (such as with the control of an orbital maneuvering vehicle or flight telerobotic servicer), operating at very low frame rates below 3 fps should be avoided unless large performance degradations are acceptable. The reduction in mean task times was found to occur at a faster rate when going from 5 fps to 3 fps than when going from 30 fps to 5 fps. This suggests that frame rates between 5 fps and 30 fps may produce performance results that would more likely meet acceptable performance criteria than frame rates below 5 fps. Thus if there is limited bandwidth available for frame rate and depending on the task, reducing frame rate from 30 fps may be acceptable until a cutoff frame rate is reached beyond which performance would be below the accepted level. It may be possible to reduce frame rate to a larger degree without harming performance by a great margin if force feedback is present. If force feedback is not present, it would probably be important to have the video transmission at a high frame rate.

Force feedback was found to make up for many of the performance degradations due to decreased feedback in the visual feedback channel. Force feedback significantly improved performance at all frame rates, and was particularly helpful at the lower frame rates. In direct viewing performance, force feedback was found to have a stabilizing effect. When subtended visual angle was decreased with force feedback, there was not a significant increase in task times. Additionally, force feedback yielded a larger improvement in performance time over the no force feedback case as subtended visual angle was decreased. Therefore whenever visual feedback conditions are extremely poor and cannot be improved, the use of force feedback could very well improve performance times to acceptable levels.

The results also suggest that force sensing was probably more important than vision for the insertion of the block into slot. Some scenarios may dictate that force feedback is impossible or undesirable, such as when used with a transmission time delay. But if force feedback is available and the task and environment do not prohibit its use, force feedback should be utilized.

As tasks become increasingly difficult, designers should not assume linear increases in task times. Task times can increase at increasing rates. This also suggests that beyond certain difficulty measures, performance time can increase beyond acceptable ranges.

For any manipulation task the effects of the different feedback variables will be unique, making broad generalizations ill advised. However the conclusions presented here indicate that task difficulty, force feedback, and the visual feedback parameters of frame rate and distance (or subtended visual angle) all can have significant effects on human performance for telemanipulation.

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