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ANTHROPOMORPHIC TELEOPERATION: CONTROLLING REMOTE MANIPULATORS WITH THE DATAGLOVE

Center Director's Discretionary Fund Final Report (Project Number 89-06)

By J.P. Hale II

Mission Operations Laboratory
Science and Engineering Directorate

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13. ABSTRACT *(Maximum 200 words)*

A two phase effort was conducted to assess the capabilities and limitations of the DataGlove, a lightweight glove input device that can output signals in real-time based on hand shape, orientation, and movement. The first phase was a period for system integration, checkout, and familiarization in a virtual environment. The second phase was a formal experiment using the DataGlove as input device to control the protoflight manipulator arm (PFMA)—a large telerobotic arm with an 8-ft reach. The first phase was used to explore and understand how the DataGlove functions in a virtual environment, build a virtual PFMA, and consider and select a reasonable teleoperation control methodology. Twelve volunteers (six males and six females) participated in a 2×3 (× 2) full-factorial formal experiment using the DataGlove to control the PFMA in a simple retraction , slewing, and insertion task. Two within-subjects variables, time delay (0, 1, and 2 seconds) and PFMA wrist flexibility (rigid/flexible), were manipulated. Gender served as a blocking variable. A main effect of time delay was found for slewing and total task times. Correlations among questionnaire responses, and between questionnaire responses and session mean scores and gender were computed. The experimental data were also compared with data collected in another study that used a six degree-of-freedom handcontroller to control the PFMA in the same task. It was concluded that the DataGlove is a legitimate teleoperations input device that provides a natural, intuitive user interface. From an operational point of view, it compares favorably with other "standard" telerobotic input devices and should be considered in future trades in teleoperation systems' designs.

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INTRODUCTION

A teleoperator can be defined as a general-purpose, dextrous, cybernetic machine.[1] The term "cybernetic" is used to exclude preprogrammed, automatic machinery, such as a dishwasher or clothes dryer. The terms "dextrous" and "general-purpose" are used to exclude human-controlled, but undextrous, machines such as remotely controlled aircraft. "Tele" is used to connote not only control across distances but across physical barriers as well. Teleoperation always includes a human operator in the loop.

Teleoperation can extend the operator's reach across great distances and into hazardous environments. It can also serve as a strength multiplier and as a means of changing the physical scale of the operator, such as for microscopic manipulations.

Many current teleoperation systems use hand controllers and switches to control the manipulator. These controls are usually not very natural nor intuitive. Much training and practice is required before an operator becomes proficient at a teleoperation task.

As the need for improved and more versatile teleoperation increases, the need for better operator interfaces increases. A promising approach in this area is towards a more "natural" interface, one that is intuitive, relying on the operator's normal movement and grasping motions as input into the system. One where the manipulator "puppets" the actions of the operator. That is, anthropomorphic in both form and function.

One promising technology is the DataGlove, a lightweight glove input device that can output signals in real time based on hand shape, orientation, and movement.

The topic of this report is the assessment and evaluation of the DataGlove as an input device for a teleoperator. Following a checkout and familiarization period in a virtual environment, the DataGlove was interfaced with the protoflight manipulator arm (PFMA), a large telerobotic arm with an 8-ft reach. Subsequently, an experiment was conducted using the DataGlove to control the PFMA. Time delay (TD) and PFMA wrist flexibility were manipulated. These data were analyzed to determine any main effects or interactions of the independent variables on performance. These data were also compared with data collected in another study that used a six degree-of-freedom (DOF) hand controller to control the PFMA in the same task.

DataGlove Description

The DataGlove was developed by VPL Research, Inc., of Redwood City, CA. It can sense and output the movement of the joints of the finger and the motion and attitude of the hand.

Finger joint flexion and extension is measured by fiber-optic cables that run the length of each finger and thumb. As a joint is bent, less light is transmitted through the cable, much as less water will flow through a bent hose. Phototransisters in the glove assembly convert these varying light signals into electrical signals that can be interpreted by a computer. The computer then computes the degree of finger flexion based on the amount of light sensed by the phototransisters. Thus, for example, as the finger flexes, less light is transmitted through the fiber-optic cables to the phototransisters. The computer then determines the degree of finger flexion that is proportional to the level of light sensed by the phototransisters.

The hand motion and attitude is sensed by a Polhemus 3Space, Isotrak, six-DOF tracking system incorporated into the DataGlove. This sensor uses a magnetic detection system to determine the hand's position, i.e., its location along the *X*, *Y*, and *Z* axes, and the hand's attitude or rotation around the *X*, *Y*, and *Z* axes, i.e., roll, pitch, and yaw.

The DataGlove can also recognize predefined "gestures." During preparation for a task, the operator can "train" the DataGlove system to remember a particular hand gesture. Then, the operator can instruct the system to output a command, or series of commands, every time that particular gesture is formed. During the conduct of the task, every time the operator forms that gesture, the DataGlove system will output the preprogrammed command or series of commands. For example, the operator could assign the gesture of "four fingers extended" to mean "move to position four." Then instead of "puppeting" the manipulator to position "four," the operator could merely extend four fingers. The DataGlove system would interpret the gesture and then move the manipulator to position four.

PFMA Description

The PFMA is a large telerobotic arm with an 8-ft reach. It has six DOF plus a seventh manually indexable DOF, making the manipulator a pseudo seven DOF mechanism. The shoulder allows yaw and pitch motions, the elbow can pitch, and the wrist can pitch, yaw, and roll. The end-effector gripper makes up the seventh DOF.

Developed in the early 1970's, the PFMA was originally intended to fly aboard the space shuttle. Because it was not developed to operate in a gravity field, but rather in space, it is counterbalanced at the shoulder, elbow, and wrist.

Based on the NASREM system design concept, the PFMA provides rate, position, hawk, and rotation control modes with high and low gains available for each. Synthetic time delays of up to 5 s are also available. The system is designed to accommodate a variety of hand controllers. This facilitated interfacing the DataGlove to the PFMA.

The operator control workstation was developed as part of the prototype ground control console for the orbital maneuvering vehicle. It includes two stacked video monitors, work surfaces, and places to mount hand controllers.

A calibrated task evaluation system has been developed to permit assessment of operator performance on a variety of teleoperation tasks. The system includes instrumented task boards that accommodate module insertion tasks and fluid exchange tasks. The instrumentation can sense and record impact and binding forces along three axes.

DATAGLOVE CHECKOUT AND FAMILIARIZATION

Prior to interfacing the DataGlove and the PFMA, a rather extensive DataGlove system checkout and familiarization effort was accomplished. Following system integration and activation, the two general areas of activity involved interacting with existing virtual environments and developing new virtual environments.

The DataGlove system comes with a "virtual control panel" computer-aided-design (CAD) file with rotating knobs, sliding levers, etc. The user is able to interact with this panel (e.g., twist the knobs and slide the levers) by "driving" a virtual wire frame hand that "puppets" the motions and gestures of the DataGlove.

There is no force-reflective feedback to the glove, so one must rely upon the computer-generated images rendered on the monitor for information on the relative locations of the virtual hand and other objects. This is further complicated by the fact that the images are two-dimensional representations of three-dimensional virtual objects. The depth dimension (i.e., into the screen) is particularly difficult to perceive and interact with since there are few depth cues available in these virtual environments. Initially, this is rather awkward and it takes practice to become proficient.

Learning to develop simple virtual environments to use with the DataGlove was not particularly difficult once the object hierarchical tree structure and coordinate systems were understood. Once some experience in developing virtual environments had been gained, a virtual PFMA (VPFMA) was developed. It was functionally accurate in that the joints (i.e., shoulder, elbow, and wrist) had the correct DOF's in the correct order. The DataGlove finger motion and/or hand motion outputs could be assigned to the VPFMA joints.

Before actually controlling the "real" PFMA with the DataGlove, operational concepts had to be developed and refined. Two concepts were considered and discarded. One involved selecting one VPFMA joint at a time, by forming a unique gesture for that joint, then rotating about the permissible axes of that joint, by rolling, pitching, and yawing the DataGlove. Positioning the end-effector by this method proved quite cumbersome.

The second method considered and discarded attempted to assign a DataGlove finger motion output to a VPFMA joint motion. As with the earlier method, positioning the end-effector by this method proved quite cumbersome. Controlling all the VPFMA DOF simultaneously, each with a different finger motion, proved virtually impossible. There was no one-to-one mapping between the finger motions and VPFMA motions. Various mapping schemes were considered and none proved intuitive enough to pursue. It became clear that to control a telerobot in this manner, the telerobot must also be anthropomorphic to some degree.

The method ultimately chosen to control the "real" PFMA was to command the end effector position and attitude by the position and attitude of the DataGlove. Hand gestures were used to enable command throughput and gains. Further detail is given in the DataGlove/PFMA experiment task section.

DATAGLOVE/PFMA EXPERIMENT

Method

Overview. Subjects performed a relatively simple teleoperation task using the DataGlove to control the PFMA. The task involved retracting, repositioning, and inserting a block from/into instrumented task boards. Both TD and PFMA wrist flexibility (F) were manipulated.

Design. The experimental design used in this study was a 2 by 3 by 2, full-factorial design with two within-subjects variables and one blocking variable, gender (G). Two independent variables were manipulated, TD for the task had three levels: 0-, 1-, or 2-s TD between command input and subsequent PFMA response. The PFMA wrist flexibility (F) had two levels: either rigid or flexible. Presen-tation order of the resulting six conditions were counter-balanced using a balanced latin square. Subjects were randomly assigned (without replacement) to one of the presentation sequences. Retraction, insertion, and slew times, as well as total task time, were collected as the dependent variables. Retraction time started as the block lost contact with the rear of the docking receptacle. Retraction time ended and slew time started as the trailing edge of the block crossed the front vertical plane of the docking receptacle. Slew time ended and insertion time started as the leading edge of the block broke the front vertical plane of the docking receptacle. Insertion time ended as the block contacted the rear of the receptacle.

Subjects. Twelve subjects (six males and six females) participated in this study on a voluntary basis.

Task. The task involved retracting a block out of a docking receptacle at one position, slewing and yawing about to a second position, inserting the block into that docking receptacle, then repeating the operations back to the first position. The PFMA was under "position" of the DataGlove. The end-effector would "puppet" the movement of the DataGlove, translating along and/or rotating about the *X*, *Y*, and *Z* axes as the DataGlove moved along and/or about these same axes. The end-effector was locked to the block for the entire task. The task involved no grasping or releasing operations, only retraction, slewing, yawing, and insertion operations.

Three gestures were employed in this task. One was an "enable" gesture. The system would only recognize commands when the thumb was bent. This gave added assurance that only hand movements that were intended as control inputs were, in fact, acted upon. For instance, if the operator suddenly moved to scratch his/her ear, the PFMA would not "puppet" this action. This gesture also permitted the operator to "ratchet" or "index" the position of the PFMA. Thus, instead of reaching far to one side to drive the PFMA to an extreme position, the operator can move the PFMA in a series of small steps by forming the enabling gesture while moving the DataGlove in the desired direction, then releasing the gesture to return to the starting point. As this is repeated, the PFMA can be commanded over great distances while keeping the DataGlove in a relatively small dynamic work envelope.

The other two gestures selected the gain for the system. One finger extended was for low gain, where a movement in the DataGlove commanded a small movement in the PFMA. Two fingers extended selected high gain, where a movement in the DataGlove commanded a large movement in the PFMA.

Materials and Apparatus. Subjects sat at the operator control workstation, developed as part of the prototype ground control console for the orbital maneuvering vehicle. Two 19-in diagonal video monitors are vertically stacked directly in front of the operator. These monitors are 22 inches from the resting eye position with the screen surface perpendicular to the eyes. The lower monitor is 30° below the resting eye position, and the upper monitor is 15° above the resting eye position. The console provides a 17-in deep work surface in front of the operator.

Two adjacent instrumented task boards were placed at a 45° angle to each other. The centerlines of the docking receptacles, into and out of which the block would be inserted and retracted, were located 56 inches above the floor. The centerline of the docking receptacle at the starting position was 25 inches to the right of the "crease" between the two task boards. The centerline of the docking receptacle at the second position was 19.5 inches to the left of the "crease."

Two cameras were positioned 56 inches above the floor, in the same horizontal plane as the centerline of the docking receptacles. One camera was positioned 57.5 inches to the right of the starting position, parallel to the face of that task board. The second camera was positioned 57.5 inches to the left of the second position, parallel to the face of that task board. The fields-of-view were adjusted just large enough to include both docking receptacles in each. The image from the starting position camera was displayed on the lower monitor. The image from the second position camera was displayed on the upper monitor.

The block was 5.75 in (height (H)) by 7.75 in (width (W)) by 6.626 in (depth (D) with a 9.5-in H by 11.5-in W flange on the face. The front and rear of the docking receptacles were instrumented to sense when a block crossed the front vertical plane of the receptacle and when a block was in contact with the rear of the receptacle.

Procedure. Prior to the day of the test sessions, each subject participated in two practice sessions. This was to both practice controlling the PFMA with the DataGlove and to become familiar and comfortable with the test environment. In the first session, subjects viewed the PFMA directly. In the second sessions, direct viewing of the PFMA was blocked, and subjects viewed the PFMA through the two video monitors. In both sessions, subjects started with no time delay, then progressed to the longer time delays. PFMA wrist flexibility was held rigid during the training sessions. Subjective self-report was the end-of-practice criterion.

Prior to the test session, each subject would read a description of the experiment (appendix A), then read and sign an informed consent form (appendix B). Then, following a short "warm-up" and acclimation period on the task, the experiment would begin. All six conditions were subsequently presented. There was a short rest period between trials while the system was reconfigured. Upon completion of the final condition, subjects completed a short questionnaire (appendix C), then were debriefed and thanked for their participation.

Results

Each experimental run yielded two retraction times, two insertion times, and two slew times for each subject. Each pair of these data were summed to yield single retraction, insertion, and slew times for a run. These, in turn, were summed to yield a total task time for a run. One insertion time was lost. The grand insertion time mean was used to fill this cell. An analysis of variance was performed on each of these four variables.

No significant main effects or interactions were found for either insertion or retraction times (tables 1 and 2, respectively).

Table 1. ANOVA summary table for insertion times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	770.870	770.870	0.023
Subjects (S)/G	10	328,180.052	32,818.052	
Within Subjects				
Time Delay (TD)	2	20,332.862	10,166.431	1.318
TD*G	2	9,736.776	4,868.388	0.631
TD*S/G	20	15,427.291	7,713.715	
Flexibility (F)	1	3,047.332	3,047.332	0.483
F*G	1	9,329.552	9,329.552	1.480
F*S/G	10	63,056.030	6,305.603	
Time Delay*Flexibillity	2	19,189.441	9,594.720	1.111
TD*F*G	2	28,541.806	14,270.903	1.653
TD*F*S/G	20	172,651.683	8,632.584	
Total	71	670,263.695	107,518.150	

Table 2. ANOVA summary table for retraction times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	18.000	18.000	0.007
Subjects (S)/G	10	24,173.000	24,170.300	
Within Subjects				
Time Delay (TD)	2	965.583	482.792	0.880
TD*G	2	594.750	297.375	0.542
TD*S/G	20	10,978.667	548.933	
Flexibility (F)	1	133.389	133.389	0.266
F*G	1	760.500	760.500	1.514
F*S/G	10	5,021.778	502.178	
Time Delay*Flexibillity	2	231.028	115.514	0.244
TD*F*G	2	1,345.083	672.542	1.423
TD*F*S/G	20	9,454.22	472.711	
Total	71	53,675.998	28,174.234	

The analysis of variance for slew time showed a significant main effect of TD, $F(2,20) = 7.478$, $p < 0.01$ (table 3). A post hoc Newman-Keuls pair-wise comparison of the means was performed at the 5-percent level of significance. There were two significantly different comparisons among the three means (CD_{N-K} (first diagonal) = 35.319 and CD_{N-K} (second diagonal) = 42,862). Slew times with no TD were significantly faster than slew times with either 1- or 2-s TD's. There was no significant differences between 1- and 2-s TD's (table 4 and fig. 1).

Table 3. ANOVA summary table for slew times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	11,050.889	11,050.889	0.247
Subjects (S)/G	10	447,795.389	44,779.539	
Within Subjects				
Time Delay (TD)	2	51,452.528	25,726.264	7.478*
TD*G	2	5,943.028	2,971.514	0.864
TD*S/G	20	68,804.778	3,440.239	
Flexibility (F)	1	2,266.889	2,266.889	0.540
F*G	1	1,300.500	1,300.500	0.310
F*S/G	10	41,970.944	4,197.094	
Time Delay*Flexibillity	2	1,417.028	708.514	0,244
TD*F*G	2	1,282.750	641.375	0.221
TD*F*S/G	20	58,041.889	2,902.094	
Total	71	691,326.612	99,984.911	

*$p = 0.0038$

Table 4. Slew time as a function of TD.

Time Delay (s)	*Mean (s)*
0	154.21
1	207.75
2	213.62

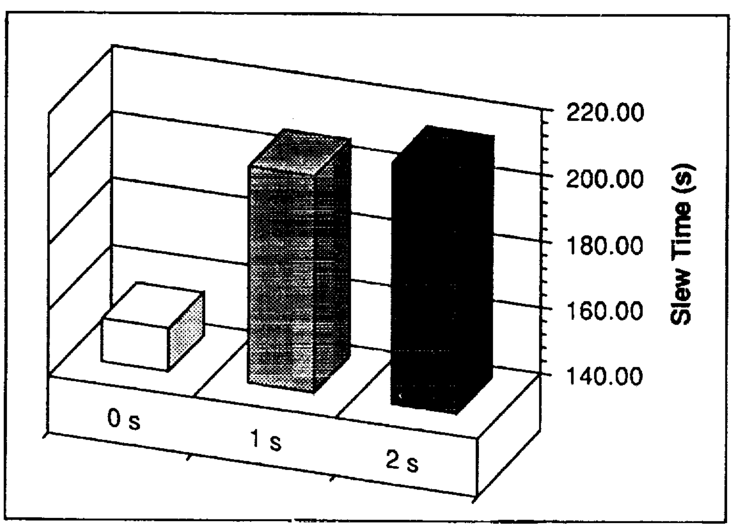

Figure 1. Slew time as a function of TD.

The analysis of variance for total time also showed a significant main effect of TD, $F(2,20) = 4.850$, $p < 0.05$ (table 5). A post hoc Newman-Keuls pair-wise comparison of the means was performed at the 5-percent level of significance. There was one significantly different comparison among the three means (CD_{N-K} (first diagonal) = 68.743 and CD_{N-K} (second diagonal) = 83.424). Total time with no TD was significantly faster than total time with a 2-s TD. There were no significant differences between 0- and 1-s TD's or between 1- and 2-s TD's (table 6, fig. 2).

Table 5. ANOVA summary table for total times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	16,549.566	16,549.566	0.108
Subjects (S)/G	10	1,535,814.744	153,581.474	
Within Subjects				
Time Delay (TD)	2	126,402.749	63,201.374	4.850*
TD*G	2	20,502.900	10,251.450	0.787
TD*S/G	20	260,648.031	13,032.402	
Flexibility (F)	1	8,329.317	8,329.317	0.403
F*G	1	11,040.732	11,040.732	0.534
F*S/G	10	206,767.168	20,676.717	
Time Delay*Flexibillity	2	19,743.253	9,871.627	0.635
TD*F*G	2	38,966.120	19,483.060	1.253
TD*F*S/G	20	311,034.413	15,551.721	
Total	71	2,555,798.993	341,569.440	

*p = 0.0192

Table 6. Total time as a function of TD.

Time Delay	*Mean (s)*
0	289.017
1	342.292
2	391.625

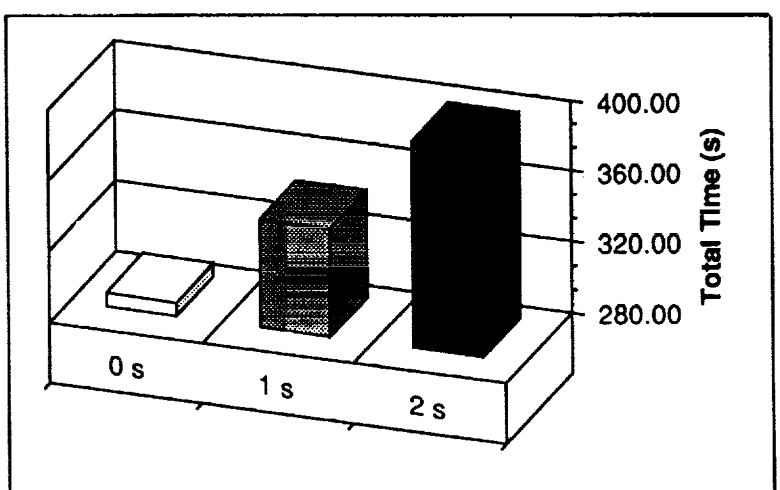

Figure 2. Total time as a function of TD.

A second set of analyses of variance was undertaken to ascertain whether or not there was any practice and/or fatigue effects occurring during the six runs within a session. These analyses included the Run*Gender interaction. There were no statistically significant main effects or interactions found in this analysis (tables 7 through 10).

Table 7. ANOVA summary table for insertion times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	770.870	770.870	0.023
Subjects (S)/G	10	32,810.522	32,818.052	
Within Subjects				
Run (R)	5	17,410.772	3,482.154	0.445
R*G	5	71,564.471	14,312.894	1.829
R*S/G	50	391,184.531	7,823.691	
Total	71	513,741.166	59,207.661	

Table 8. ANOVA summary table for retraction times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	18.000	18.000	0.007
Subjects (S)/G	10	24,173.000	2,417.300	
Within Subjects				
Run (R)	5	1,533.833	306.767	0.598
R*G	5	2,304.167	460.833	0.898
R*S/G	50	25,647.000	512.940	
Total	71	53,676.000	3,715.840	

Table 9. ANOVA summary table for slew times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	11,050.889	11,050.889	0.247
Subjects (S)/G	10	447,795.389	44,779.539	
Within Subjects				
Run (R)	5	15,293.611	3,058.722	0.813
R*G	5	29,015.111	5,803.022	1.542
R*S/G	50	188,171.611	3,763.432	
Total	71	691,326.611	68,455.604	

Table 10. ANOVA summary table for total times.

Source	*df*	*Sum of Squares*	*Mean Square*	F
Between Subjects				
Gender (G)	1	16,549.566	16,549.566	0.108
Subjects (S)/G	10	1,535,814.744	153,581.474	
Within Subjects				
Run (R)	5	68,883.304	13,776.661	0.896
R*G	5	165,802.767	33,160.553	2.157
R*S/G	50	768,748.613	15,374.972	
Total	71	2,555,798.994	232,443.226	

Responses to the questionnaire were reduced and coded. Means or frequencies were computed for these questions (table 11). Correlation coefficients were computed among selected questions and reported fatigue, mean total task time, and gender.

Table 11. Descriptive statistics for the questionnaire.

Question	Response*
Frequency of playing video games†	1
Frequency of using a mouse	2
Level of difficulty operating the PFMA	
with no time delay	1
with 1-s time delay	2
with 2-s time delay	2
with a rigid wrist	2
with a flexible wrist	2
Level of fatigue at completion	2
Overall impression of DataGlove	4
Adequate training period‡	Y
Current emotion/physical condition	4

*Responses are 1 = low / 5 = high, except as noted below
†0 = none / 5 = high
‡All subjects responded yes.

Correlations between questions concerning perceived difficulties encountered with the independent variable manipulations and reported fatigue (table 12) indicate only a relatively low correlation between perceived difficulties with 1-s TD and reported fatigue ($R = 0.406$, $R^2 = 0.165$). Little or no correlation was found between reported fatigue and perceived difficulties encountered with no TD ($R = 0.135$, $R^2 = 0.018$), 2-s TD ($R = 0.200$, $R^2 = 0.040$), a rigid wrist ($R = 0.070$, $R^2 = 0.005$), and a flexible wrist ($R = 0.212$, $R^2 = 0.045$).

Table 12. Correlations between perceived difficulties and reported fatigue.*

Question	Fatigue Level at Completion
Level of difficulty operating the PFMA	
with no time delay	0.135/0.018
with 1-s time delay	0.406/0.165
with 2-s time delay	0.200/0.040
with a rigid wrist	0.070/0.005
with a flexible wrist	0.212/0.045

*R/R^2

Little or no correlation was found between mean total task time (table 13) and questions concerning experience with video games ($R = 0.005$, $R^2 = 2E{-}5$) or a mouse ($R = 0.137$, $R^2 = 0.019$), reported fatigue ($R = 0.286$, $R^2 = 0.082$), overall impression of the DataGlove ($R = 0.104$, $R^2 = 0.011$), and perceived adequacy of training (all subjects responded "yes"). Mean total task time did correlate moderately with reported emotional and/or physical condition ($R = 0.638$, $R^2 = 0.406$).

Table 13. Correlations between session mean scores and selected questionnaire responses.*

Question	Session Mean Score
Frequency of playing video games	0.005/2E–5
Frequency of using a mouse	0.137/0.019
Level of fatigue at completion	0.286/0.082
Overall impression of DataGlove	0.104/0.011
Adequate training period	†
Current emotion/physical condition	0.638/0.406

*R/R2

†All subjects responded yes.

Finally, correlations were computed between gender and the questionnaire responses (table 14). Relatively low correlations were found between being female and perceived difficulties with a 2-s TD (R = 0.385, R^2 = 0.148) and a rigid wrist (R = 0.338, R^2 = 0.114). Relatively low correlations were also found between being female and reported fatigue level (R = 0.346, R^2 = 0.120) and overall impression of the DataGlove (R = 0.302, R^2 = 0.091). Little or no correlation was found between gender and questions concerning experience with video games (R = 0.140, R^2 = 0.020) or a mouse (R = 0.124, R^2 = 0.015), or perceived difficulties with no TD (R = 0.130, R^2 = 0.017), a 1-s TD (R = 0.090, R^2 = 0.008), or a flexible wrist (R = 0.087, R^2 = 0.008).

Table 14. Correlations between gender and questions.*

Question	Gender
Frequency of playing video games†	0.140/0.020
Frequency of using a mouse	0.124/0.015
Level of difficulty operating the PFMA	
with no time delay	0.130/0.017
with 1-s time delay	0.090/0.008
with 2-s time delay	0.385/0.148
with a rigid wrist	0.338/0.114
with a flexible wrist	0.087/0.008
Level of fatigue at completion	0.346/0.120
Overall impression of DataGlove	0.302/0.091
Adequate training period	†
Current emotion/physical condition	0.000/0.000

*R/R2
†All subjects responded yes.

Discussion

The primary objective of this experiment was to determine the effects of TD and PFMA wrist flexibility on the ability of a user to accurately and effectively operate a telerobot with a DataGlove.

As expected, TD had a significant effect on performance. Any TD (i.e., 1 or 2 s, in this experiment) increased slew times. Interestingly, TD had no significant effects on either insertion or retraction times. When all of these times are summed together, the distinction between 0- and 1-s TD's is blurred. That is, only the 2-s TD was significantly different from no time delay. A review of the data shows little change from slew time to total time for their respective differences between 0- and 1-s TD's. The slew time difference between 0- and 1-s TD is 53.542 s. The total time difference between 0- and 1-s TD is 53.275 s. The 0- to 2-s TD comparison shows a slew time difference of 59.417 s, but a total time difference of 102.608 s.

This suggests that the slewing and gross positioning components of the total teleoperations task are more sensitive to even relatively short time delays (evident at a 1-s TD), than the relatively straightforward insertion and retraction components. This experiment showed no significant main effect of TD on insertion and retraction times, but TD was only up to 2 s. It would appear, from the review of the "differences" data above, that insertion and retraction times would eventually be significantly degraded as TD is further increased.

PFMA wrist flexibility had no significant main effect on the ability of the subject to accurately and effectively operate the PFMA with a DataGlove. Although not particularly surprising for slewing times, it was thought that retracting and especially inserting the block into the docking receptacle would be hindered by a rigid wrist due to the greater fine alignment accuracy required. The rigid wrist should be less forgiving and would bind if not correctly aligned.

A concerted effort was made for this experiment to adequately train the subjects before starting the data collection. This effort was apparently successful, as there were no significantly different times among runs within the session. In addition, all subjects indicated on the post-session questionnaire that they had an adequate training period.

Even if this had not been the finding, one must always anticipate carry-over effects from one condition to another in all within-subject's experiments, and design accordingly. In this experiment, a balanced Latin square was employed to counter-balance the sequences of condition presentation. With this technique, each condition precedes and follows every other condition an equal number of times, thus carry-over effects and differential transfer effects are decoupled from the independent variables of interest.

Questionnaire responses indicate a favorable overall impression of the DataGlove. In terms of subjective responses to the independent variables, subjects reported the same relatively low level of difficulty in operating the PFMA under the various conditions. Although this is supported by the objective, experiment data for the PFMA wrist flexibility manipulation (i.e., no significant main effect), the TD manipulation did significantly degrade performance.

In all fairness, part of the increase in performance time can be directly attributed to the actual TD. If the entire sequence and timing of commands under the no-time delay condition were recorded, then sent open loop for execution using, for example, the 2-s TD, the total task time would be increased by 2 s (i.e., time from first command sent to receipt of feedback of last command execution).

To the extent the operator can accurately anticipate or predict the system response, commands can be sent, essentially open loop, while the operator corrects for error with "stale" information. Movements may be somewhat slower than with no TD, but they are essentially still continuous.

In most cases, however, this is not possible, particularly with longer TD's. Others have found that operators switch to a "move-and-wait" strategy, at some point, as TD increases (e.g., Ferrell[2]). Each "move" is simply a series of commands sent open loop. Thus, depending on the number of commands per "move" before a "wait" is needed, the total task is partitioned into a number of "moves," each adding a component of the TD to the total task time. The total time, then, includes the cumulative "waits" following each "move."

Increases in performance times, as TD's increase, can thus be attributed to several interrelated components, in addition to the actual delay. One component, as the delay increases, is the ability of the operator to anticipate or predict system response. At some level of TD, the operator changes to a "move-and-wait" strategy, and size and number of the "move" partitions become factors.

Thus, the finding of a main effect of TD, by itself, is not necessarily noteworthy. The nature of the finding (i.e., considering the analysis of variance and the post hoc test results) does suggest that the subjects may have been operating in both the anticipatory "open loop" mode and in the "move-and-wait" mode at different times during the experiment. The TD finding, then, suggests that the DataGlove can be an effective telerobotic input device for a variety of operational modes and strategies.

Only one relatively high correlation stands out. The reported current emotional and/or physical condition and the session mean score are correlated, with over 40 percent of the variation of each "explained" by the other. This appears to add support to the importance of a positive mental attitude on performance. If, in fact, this should turn out to be a general finding in teleoperations, or for any man-in-the-loop control task for that matter, then selection and, more importantly training, would do well to attend to this factor.

A secondary objective of this effort was to begin the development of an objective, operational data base on the utilization of the DataGlove in teleoperations. This data base can then be compared with the more substantial data base of other teleoperations input devices. One such set of data comes from a similar study that was conducted using the same task and equipment, including the PFMA, but with a six-DOF hand controller (K.D. Garcia, personal communication, November, 1990). Common features include the same TD's and the PFMA wrist flexibility manipulation. Comparable dependent variables are the insertion and slewing times.

As with this study, the six-DOF study found a main effect of TD for slewing times, $F(2,22) = 16.812$, $p < 0.001$. A post hoc Newman-Keuls pair-wise comparison of the means was performed at the 5-percent level of significance. All three comparisons were significantly different (CD_{N-K} (first diagonal) = 39.311 and CD_{N-K} (second diagonal) = 47.614). Also, as with this study, there was no main effect of TD for insertion times, nor main effect of PFMA wrist flexibility for either slewing or insertion times.

The magnitude of the times also compare favorable. Because of the differences between these two studies (e.g., different experimenters, different groups of subjects, different instructions, etc.), a full quantitative combined analysis is probably not acceptable, however, a qualitative comparison of the means is possible.

Slew times as a function of TD (table 15) indicates that the DataGlove compares favorably with the six DOF. The six DOF appears faster with no TD, but the order is reversed at a 2-s TD. Even though, without a quantitative analysis, no definitive statement can be made as to presence or absence of any statistically significant differences, it would appear that the DataGlove is comparable, at least in terms of order of magnitude, with the six DOF. A similar statement can be made for the comparison of the insertion times using the DataGlove and the six DOF (table 16).

Based on the results and experiences of this experiment, it would appear that the DataGlove is capable of being gainfully employed in support of teleoperations. The most significant result was that the DataGlove could, in fact, control a telerobot. The fact that it did so both effectively and efficiently only serves to enhance its potential applications.

Table 15. Mean slew times as a function of TD for DataGlove and six DOF.

Time Delay (s)	DataGlove Mean (s)	Six DOF Mean (s)
0	154.21	131.431
1	207.75	198.153
2	213.62	240.354

Table 16. Mean insertion times for DataGlove and six DOF.

DataGlove Mean (s)	Six DOF Mean (s)
121.12	115.91

CONCLUSIONS

The goal of this effort was the assessment and evaluation of the DataGlove as an input device for a teleoperator.

A two-phase effort was conducted to assess the DataGlove's capabilities and limitations. The first phase was a period for system integration, checkout, and familiarization in a virtual environment. The second phase was a formal experiment using the DataGlove as an input device in teleoperations.

The first phase was used to explore and understand how the DataGlove functions in a virtual environment, build a VPFMA, and consider and select a reasonable teleoperation control methodology.

The formal experiment demonstrated that the DataGlove can, in fact, control a telerobot. The study showed that not only can the DataGlove be used as a teleoperation input device, but that it is a very capable, natural, and intuitive interface for teleoperation. The training period to proficiency is relatively short, and the task completion times and accuracy compare favorably to the more commonly used teleoperation controllers. Further studies and real-world applications are clearly indicated for this exciting new technology.

Taken together, these efforts indicate that the DataGlove is an effective means of operating a telerobot. Because it is a natural and intuitive user interface, initial and proficiency training times can be reduced. With "indexing," its dynamic work envelope can be minimized. This can be particularly important in limited volume teleoperations work environments (e.g., Space Station *Freedom* (S.S. *Freedom*) cupola).

Interfaced with an anthropomorphic, dextrous end-effector, this combination could be used in lieu of a glovebox, where the end-effector is inside the sealed environment and is controlled by the DataGlove from outside the sealed environment. This application would be especially valuable where leaks into and out of the sealed environment must be prevented. Gloveboxes, by their very nature, always leak in one direction. Another aspect of this application is the elimination of the large gloves used in gloveboxes. In areas where stowage volume is limited (e.g., S.S. *Freedom*), reducing or removing the inventory requirements for these consumables is a benefit.

In summary, the DataGlove faired well in this evaluation. It appears to be a legitimate teleoperations input device that provides a natural, intuitive user interface. From an operational point-of-view, it compares favorably with other "standard" telerobotic input devices. It should be considered in future trades in teleoperation systems' designs.

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2. Ferrell, W.R.: "Remote Manipulation With Transmission Delay." IEEE Transactions of Human Factors in Electronics, Cambridge, Massachusetts Institute of Technology, 1965.

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APPENDIX A

Experiment Description

EXPERIMENT OVERVIEW

The purpose of this experiment is to examine performance on a teleoperation task. In this experiment, you will be asked to operate the Proto-Flight Manipulator Arm (PFMA) using the DataGlove under a variety of conditions. Following a short warm-up period, six data collection trials will begin. The data collected during your trials will be treated with anonymity.

Two parameters will be manipulated during this experiment. These are: **Time Delay** (0,1,and 2 seconds) and **PFMA Wrist Flexibility** (rigid and flexibility). All possible combinations of these variables will be presented. There will be a short rest period after each trial, during which the experimenters will reconfigure the PFMA for the next trial. Upon completion of the last trial, you will be asked to complete a short questionnaire. The entire experiment is expected to last approximately 60 minutes.

The research team consists of:

1. Tom Bryan, Control Electronics Branch, 544-3550
2. Cindy Coker, Control Electronics Branch, 544-3541
3. Joe Hale, Man-Systems Integration Branch, 544-2193
4. Elaine Hinman, Control Electronics Branch, 544-3519
5. Gina Klinzak, New Technology, Inc. , 461-6464
6. Pam Nelson, Control Electronics Branch, 544-3645

The research is sponsored by NASA, Marshall Space Flight Center, Huntsville, Alabama.

Attached for you to read and sign is an informed consent form. This informs you that you have the right to decline to participate at any point in the experiment. Participation is voluntary.

A member of the experimental team will answer any questions you may have. However, in cases that may affect the outcome of the experiment, the team member may delay a detailed answer until you have completed the experiment. You are requested to refrain from discussing the experiment with other study participants until after their experiment session, as this may influence their performance in some manner.

Finally, we want to point out that the task is not difficult. The experiment is not designed to test your skill. We are only interested in how your performance may vary based on the different trial conditions. Furthermore, as indicated earlier, the data will be treated with anonymity.

APPENDIX B

Informed Consent Form

PARTICIPANT'S CONSENT

As a participant in this experiment, you have certain rights. The purpose of this form is to make you aware of these rights and obtain your consent to participate. Your participation is voluntary.

1. You have the right to stop the experiment in which you are participating at any time if you feel that it is not agreeable to you.

2. You have the right to see your data and withdraw it from the experiment, if you feel that you should. In general, data are processed after all runs are completed. In this experiment, we can provide you with some qualitative information immediately after the experiment. Subsequently, all data are treated with anonymity. Therefore, if you wish to withdraw your data, you must do so immediately after your participation is completed.

3. You have the right to be informed on the results of the overall experiment. If you wish to receive information on the results, please include your address with your signature below. A summary will be sent to you.

We hope you will find the experiment a pleasant and interesting experience. The research team involved greatly appreciates your help as a participant. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. We will do our best to answer them, subject only to the constraint that we do not want to pre-bias the experimental results.

Your signature below indicates that you have read the above stated rights and that you consent to participation. If you include your printed name and address below, a summary of the experimental results will be sent to you.

____

____

____

Print name and address if you wish to receive a summary of the experimental results.

____

Signature

____

Witness' Signature

APPENDIX C

Questionnaire

QUESTIONNAIRE

DataGlove Test Questionnaire

Subject Number: ________

1. Do you play video games?

   yes ☐ no ☐

   If yes, how often do you play?

Daily	4-5 times per week	1-2 times per week	Once per month	Occasionally (every few months)
☐	☐	☐	☐	☐

2. Do you use a mouse?

   yes ☐ no ☐

   If yes, how often?

Daily	4-5 times per week	1-2 times per week	Once per month	Occasionally (every few months)
☐	☐	☐	☐	☐

3. What was your level of difficulty in operating the PFMA?

	High		Moderate		Low
With no time delay	☐	☐	☐	☐	☐
With 1 second time delay	☐	☐	☐	☐	☐
With 2 second time delay	☐	☐	☐	☐	☐
With a rigid wrist	☐	☐	☐	☐	☐
With a flexible wrist	☐	☐	☐	☐	☐

4. How would you judge your fatigue level when finished?

No Fatigue		Moderate		Highly Fatigued
☐	☐	☐	☐	☐

Subject Number: ________

Personal Observation

What was your overall impression of the DataGlove?

- ☐ Strongly Like
- ☐ Like
- ☐ Neutral
- ☐ Don't Like
- ☐ Strongly Dislike

Do you feel you had an adequate training period? ☐ yes ☐ no

How do you feel today (eg. emotional/physical)?

- ☐ Excellent
- ☐ Good
- ☐ Only Fair
- ☐ Poor
- ☐ Terrible

Do you have any comments or suggestions regarding the DataGlove (e.g., comfort, responsiveness, improvements, other applications)?________________

____

____

____

____

____

APPROVAL

ANTHROPOMORPHIC TELEOPERATION: CONTROLLING REMOTE MANIPULATORS WITH THE DATAGLOVE

By J.P. Hale II

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

Harvey Golden

C.S. GRINER
Director/Mission Operations Laboratory

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