

Evaluation of an Advanced Operator Interface for Teleoperation of a Satellite Servicing Spacecraft

Kevin P. Davis*, Dr. David L. Akin**

*Space Systems Laboratory, University of Maryland, USA
e-mail: kevpdavis@ssl.umd.edu

**Space Systems Laboratory, University of Maryland, USA
e-mail: dakin@ssl.umd.edu

Abstract

Teleoperation of a satellite servicing spacecraft is a challenging task for a human operator. On-orbit operations are further complicated by communications time delays between the ground and spacecraft. Operator performance in the presence of time delay can be improved with the use of a graphical simulation of the robot. By displaying the robot's commanded position, graphical simulation can also mitigate some effects of time delay. This work implemented a visualization tool and commanded display to assist operation of a remote dexterous manipulator. A Fitts' Law experiment was designed to determine the effectiveness of the commanded display in ameliorating the effects of time delay for robot positioning. The experiment was conducted with a 6 degree of freedom manipulator over a range of time delays from 0 to 6 seconds. The experimental results were analyzed to assess the reduction of task completion time.

1 Introduction

The University of Maryland Space Systems Laboratory (SSL) has partnered with the NASA Goddard Spaceflight Center (GSFC) Satellite Servicing Capabilities Office (SSCO) to study the teleoperation of a robotic satellite servicing spacecraft. The SSL has a long history of developing advanced robotics systems for on-orbit servicing, assembly, and inspection, as well as extensive experience performing space human factors testing. This work builds on past studies of teleoperation tasks at the SSL for the Ranger project. Additionally, many other studies have examined a variety of operator interfaces and the effects of time delay in teleoperation.

On-orbit robotic servicing requires human operators to remotely control dexterous manipulators. A robot operator must be able to perform servicing tasks in the presence of a communication time delay between the operator and remote servicer. For communicating with a spacecraft in low Earth orbit (LEO), the minimum round trip time delay is 0.4 seconds, due to the speed of light. In prac-

tice, however, delays upwards of six seconds are typical [4][15]. The delay between sending a command and seeing the resulting motion impedes the operator's ability to perform effective realtime teleoperation of the robot[14]. The lack of immediate feedback starts to cause them to decorrelate the feedback from their input at round trip delays as low as 0.3 seconds [7]. They lose the ability to compensate for the delay and transition to a move-and-wait strategy for delays above one second [1][5]. In the move-and-wait strategy, the operator will deflect their hand controllers slightly, and then wait to see the result before moving the hand controller again, significantly increasing the time needed to complete tasks.

A graphical simulation can provide immediate feedback, restoring the operator's ability to perform effective realtime control [9][15][16]. Extensive previous work has focused on the use of predictive displays, which overlay a system's future state on an actual display, such as shown in Figure 1.

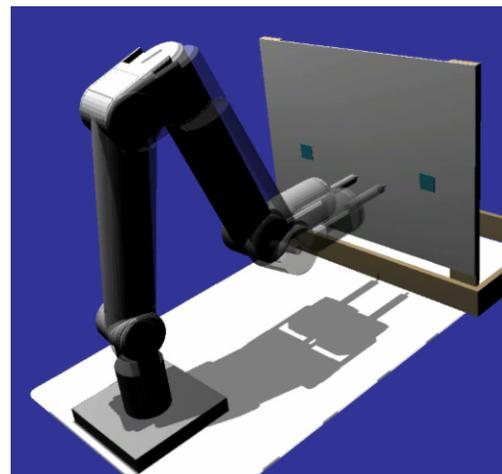


Figure 1. Example of a Transparent Overlay used to Display a Manipulator's Future Position

A general predictive display algorithm is illustrated in Figure 2. In a predictive display, operator input is simultaneously sent to the physical system and a simulated system. The computed state of the simulated system is immediately displayed to the operator. The resulting state from the physical system can then be verified after the duration of the round-trip time delay. Noyes developed one of the first predictive displays for a 6DOF telemanipulator in order to compensate for video with low update rates [13]. Mar later demonstrated a similar system with communication time delay. [12]. Predictive displays have been shown to decrease task completion times at high time delays [8][9][12][16]. However, because the user input is simply passed into both the predictive simulation and to the actual system, the predictive system may need periodic recalibration [8].

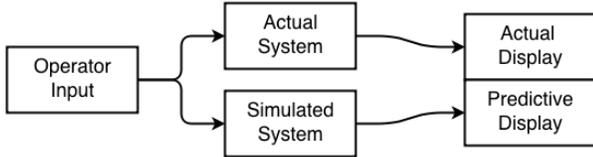


Figure 2. General Predictive Display Algorithm

Early predictive systems were open-loop, requiring fine adjustment from the operator to close the control loop. Advances in technology led to increased local autonomy in robotic systems, in turn allowing more sophisticated levels of supervisory control. More sophisticated systems allowed operators to generate scripted or symbolic commands for robotic systems to autonomously follow [1][11]. Conway used a display to generate commands for a manipulator using the concept of position and time clutching [2]. The operator could disengage the time clutch and control the simulation faster or slower than they would control the real robot to set waypoints for the robot to follow. The commands would then be sent to the real robot, which would interpolate between the waypoints as it moved to the commanded positions.

The use of a commanded display for teleoperation in realtime was explored by Lane [8]. A simulation generates the future commanded position of the robot, which is displayed immediately to the operator. Given feasible commands, the physical robot will move to the commanded position after it receives the delayed command. The general algorithm for this is given in Figure 3. The commanded display and actual, telemetry based display are overlaid in a single view. The view may be video or a purely graphical simulation. Lane demonstrated a commanded display at delays of up to six seconds, and found very high mitigation of time delay effects. However, Lane’s entire robotic system, including the actual system, was purely simulated. This work extends Lane’s study and

demonstrates the commanded display as a realtime teleoperation tool on a physical robotic system.

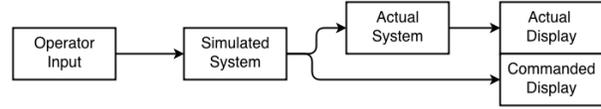


Figure 3. General Commanded Display Algorithm

The commanded display algorithm used in this study is given in 4. The operator commands the Cartesian rate of the robot’s tool-tip, \dot{x}_c , with a set of hand controllers, where x_c is the robot tool-tip’s commanded position. The purely kinematic simulation generates the commanded joint pose, q_c . The commanded pose is then simultaneously sent to the actual system and the commanded display. The commanded display is a graphical model of the arm that is updated by the commanded pose, allowing the operator to immediately see the results of their input. The joint command is delayed by the communication distance. The robot receives the delayed joint command, q'_c , and updates its desired joint position, q_d . The robot then sends its current measured joint pose, q_m , back to the operator. The measured joint pose passes through the communication time delay and becomes the delayed measured joint pose, q'_m . The delayed pose then updates the operator’s actual display. After the operator issues a command, the commanded display shows the result immediately. After the duration of the round-trip time delay has passed, the actual arm converges to the commanded position.

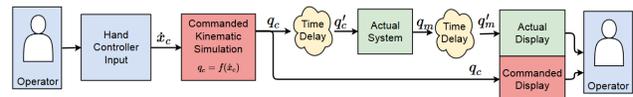


Figure 4. Commanded Display Algorithm with Time Delay

2 Experiment

This work utilized a Fitts’ Law task to investigate the effectiveness of the commanded display for positioning a manipulator in the presence of time delay [6]. The goal of a Fitts’ Law task is to move back and forth between two targets, tapping each one in turn. Fitts defined the Index of Difficulty, given by:

$$ID = \log_2(2 * D/W) \quad (1)$$

where ID is the Index of Difficulty, D is the distance between targets, and W is the target width. The ID character-

izes the difficulty of a task, and is a relationship between the target size and separation. According to Fitts' Law, a task with smaller targets at wider separations will take longer to complete than with larger targets spaced closer together. Four target configurations were chosen for this study, two sizes and two separations. Two configurations were chosen to have the same ID in order to determine if size or separation was a larger factor.

The task was repeated with each target configuration at six different time delays, and the use of a commanded display was compared to teleoperation without a delay mitigating factor. Table 1 lists the task variables considered, and the overall test matrix is listed in Table 2.

Table 1. Fitts' Law Task Summary

Task: Fitts' Law Task	
Independent Variables:	
Time Delay:	0.0, 0.33, 1.0, 2.0, 4.0, 6.0 seconds
Display Method:	None, Commanded
Target Size:	2.0, 4.0 in
Target Separation:	11.0, 25.0 in
Dependent Variable:	
Task Completion Time (seconds)	
Total Test Cells:	48

Table 2. Fitts' Law Task Test Matrix

Display Method	No Overlay				Commanded			
	11.0		25.0		11.0		25.0	
Target Separation (in)								
Target Size (in)	2.0	4.0	2.0	4.0	2.0	4.0	2.0	4.0
Time Delay (s)								
0.000	×	×	×	×	×	×	×	×
0.334	×	×	×	×	×	×	×	×
1.000	×	×	×	×	×	×	×	×
2.000	×	×	×	×	×	×	×	×
4.000	×	×	×	×	×	×	×	×
6.000	×	×	×	×	×	×	×	×

Five test subjects participated in the study. Each had some previous experience operating robotic systems, and four had previously operated a robotic manipulator.

2.1 Setup

Figure 5 shows the overall view of the physical and virtual robot workspaces used for this task. The physical workspace includes the robot arm, task board, targets, and contact sensors. The virtual environment contains models of the key workspace elements, including

the robot arm, task board, and targets. The targets on the task board were contact sensors designed to automatically detect successful target positioning. Detection occurred when a grounded contact on the robot tool-tip made contact with the target plate. Contacting the targets pulled the target plates to ground, which was detected by an Atmega328 microcontroller. After successful contact, the microcontroller toggled two lamp indicators, which gave the operators a visual confirmation of successful positioning. During the task, the task software logged the time between each full traverse between targets.

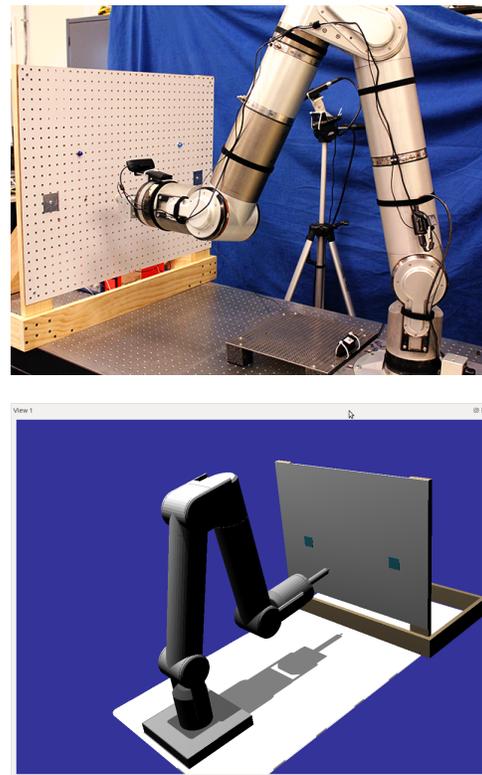


Figure 5. The Physical (Top) and Virtual (Bottom) Task Sites.

The operator controlled the arm from the workstation shown in Figure 6. The workstation consists of two monitors and a pair of three DOF hand controllers. The screen on the left showed the visualizer while the right screen displayed camera video. Each screen contained an orthogonal pair close to the task board, and an overall view showing the entire robot. The video view had an additional tool-tip camera, which was replaced in the visualizer with a closer view of the task board. The left hand controller controlled the translational rate of the end effector, and the right hand controller controlled the rotational rate.

The operator had the visualizer available during each



Figure 6. Workstation with Visual Interfaces and Input Device.

task. Figure 7 shows how an operator would use the commanded display to position the robot on a target. The solid model showed the actual display, updated by the delayed robot telemetry. The transparent overlay was the commanded display. The operator was able to control this model in realtime while the actual display lagged behind.

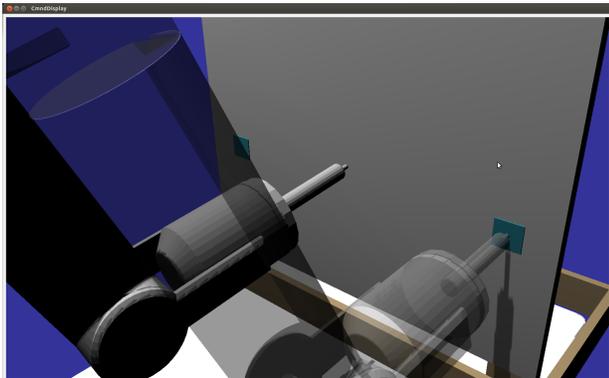


Figure 7. Using the Commanded Display to Position the Robot Tool-tip Against the Target

Figure 8 illustrates the overall data flow and network setup. There were two sides of the network: the workstation side and the remote side. The workstation contained the main workstation computer and hand controller server. These systems provided the main operator interfaces. The workstation computer was also used to sync and log the telemetry and target detection data. The remote network consisted of the robot's Data Management Unit (DMU) and a task server. The DMU ran the robot control software, and the task server streamed video feeds to the workstation using the VLC media player. The task server also continuously streamed the states of the targets.

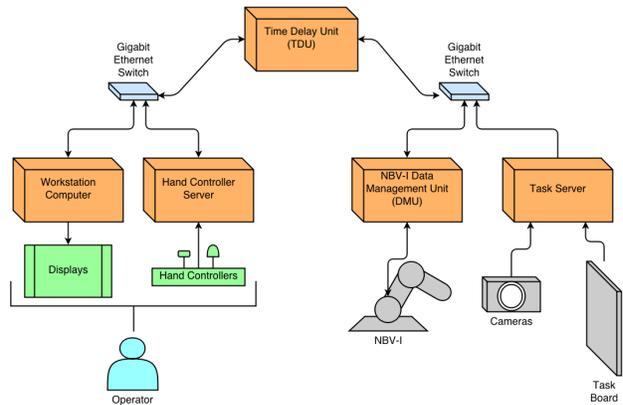
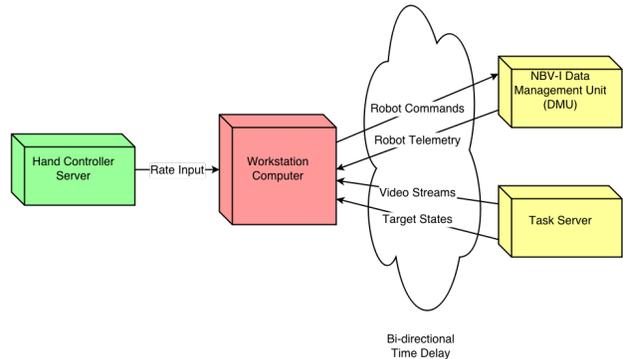


Figure 8. Data Flow (Top) and Network Diagram (Bottom) of the System

The Time Delay Unit (TDU) introduced the communication time delay. The TDU was a Linux workstation with two Network Interface Cards. One NIC was connected to the network switch on the remote network, and the other connected to the workstation network switch. The two ethernet interfaces were bridged in order to link the two networks together. The netem packet scheduling utility provided the actual time delay emulation. A fixed time delay was added on each interface, simulating the bi-directional time delay. One half of the total round-trip time delay was added to each direction of communication. It should be noted that the video streaming added approximately 100ms to the delay of the video.

2.2 Procedures

Each new test subject was first introduced to the task. The test director explained the task itself, the variables, the interfaces they would be using, and how data would be collected. After the initial familiarization, the subject performed a series of training tasks. They learned how to use the hand controllers to position the arm, and gained

familiarity with the available virtual and video views. The training tasks served not only to teach the subjects how to operate the arm, but also to move them down the learning curve. The subject performed these tasks until the rate of improvement leveled off. This significantly improved task completion times, and prevented learning effects from introducing errors into the test data.

A test subject moved onto the main test matrix for the experiment after the training period. The tests began at no time delay, and progressively increased to six seconds. At each delay treatment, the subject started with the No Overlay display method, and performed the task for all four target configurations. They then switched to the commanded display, and repeated the task for each target configuration. In order to prevent undue operator fatigue, the subjects performed the tests over multiple sessions. The total testing time ranged between six and eight hours, with individual test sessions not exceeding three hours.

The data was then analyzed for the effects and interactions of the variables. Analysis of variance was performed to determine the statistical significance of these effects.

3 Results

Figure 9 shows a comparison of the average completion time due to time delay and display method. It plots both a performance curve and a comparison with standard deviation error bars. The main effects of both time delay and display method were statistically significant to the $p < 0.01$ level. The interaction between display method and time delay was also statistically significant to the $p < 0.01$ level.

The plots show clear reductions in performance degradation for time delays of two seconds and higher when using the commanded display. The plots also indicate improvements over the no overlay case at all time delays, however improvement at low delay treatments was not significant. Table 3 summarizes the improvement and impact reduction for the high delays when using the commanded display. The Improvement column indicates the absolute improvement as compared to the No Overlay treatment for a given time delay. The Delay Mitigation column indicates the reduction in performance degradation due to time delay. The performance degradation here is defined as the additional time it takes to complete a task, as compared to no delay. These results indicate that the commanded display eliminated nearly all performance degradation due to time delay for this task.

It had been the original intent of this work to analyze the task completion time as a function of the Index of Difficulty. However, the target size did not have a statistically significant effect. The target size was also examined for a possible interaction with the display method. However, as shown by Figure 10, the target size had no discernible

Table 3. Improvement Using Commanded Display

Time Delay (s)	Improvement (%)	Delay Mitigation (%)
2.0	48	96
4.0	64	96
6.0	67	93

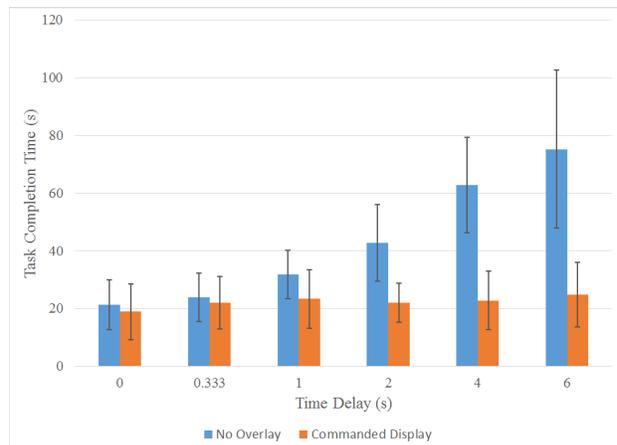
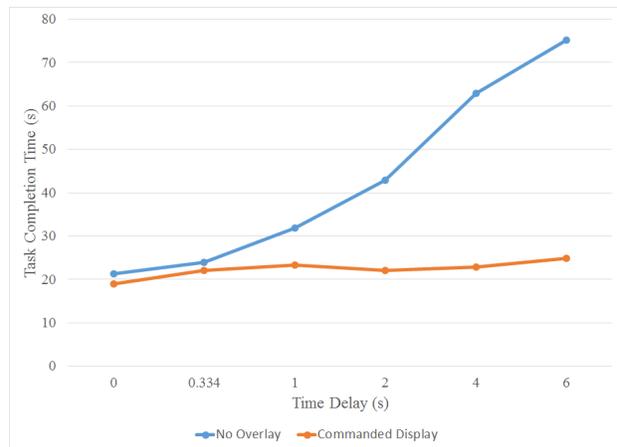


Figure 9. Performance(top) and Standard Error (bottom) Comparison of Time Delay by Display Method over Combined Target Separation and Size.

effect. Its main effects were not statistically significant.

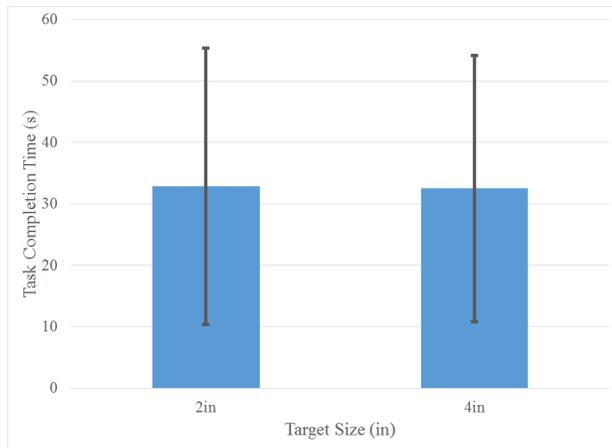


Figure 10. Comparison of Target Size over Combined Time Delay, Display Method, and Target Size and Separation.

The separation between targets, however, had a statistically significant effect on completion time to the $p < 0.01$ level. The completion time due to separation is plotted with standard deviation error bars in Figure 11.

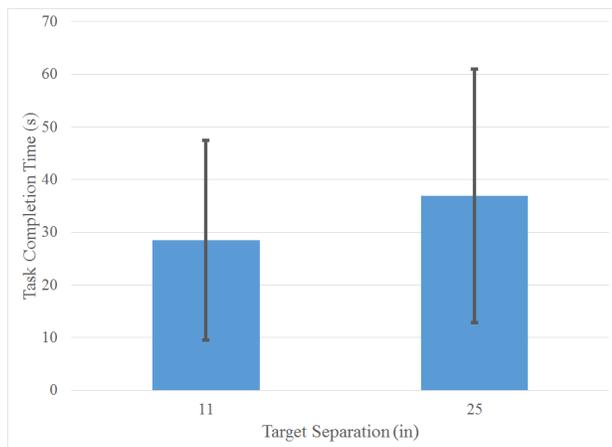


Figure 11. Comparison of display method over combined target configurations.

Of greater interest was a possible interaction between target separation and display method. Figure 12 shows the average completion time as a result of separation for each display method. No significant interaction between these variables was found. This suggests that the commanded display was equally effective for both the gross and fine

movements required for this positioning task.

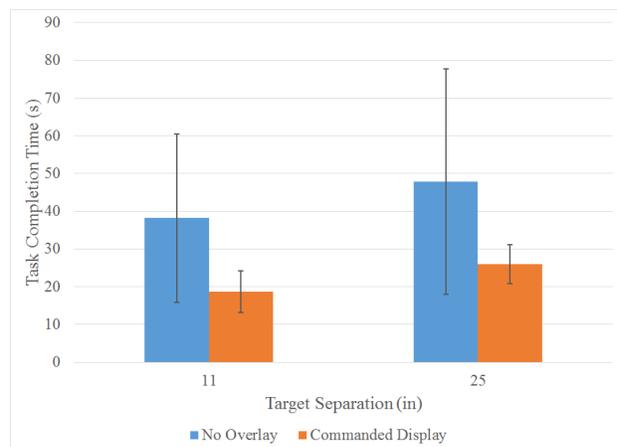
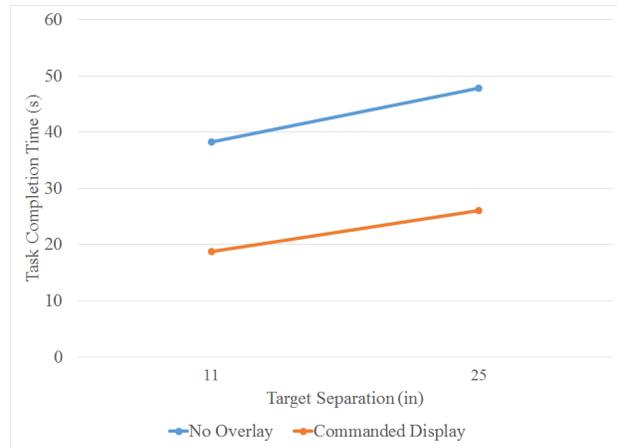


Figure 12. Comparison of Target Separation by Display Method over Combined Time Delay and Target Size and Separation.

4 Discussion

Time delay was clearly a significant factor in this experiment. The results show a strong relationship between time delay and the task completion time. As the delay increased, the task performance suffered. For the highest delay treatments, subjects had completion times several times higher than the no delay treatment. The use of the commanded display, however, nearly eliminated this performance decrease.

The study clearly demonstrates the effectiveness of the commanded delay at ameliorating time delay effects for a robot positioning task. At high delay treatments, the commanded display reduced the completion time due

to delay by upwards of 90%. This strongly corroborates Lane's study, which found improvements in the range of 84-91% [8].

The results indicate a slightly larger amelioration of time delay with the commanded display than Lane found for a similar positioning task. This result was somewhat unexpected. Rather, it was expected that testing on a physical system would introduce some performance degradation due to real-world system dynamics. In comparison, Lane's study employed a purely kinematic simulation with no system dynamics. It could be argued that this discrepancy is simply not significant, but there are several possibilities that warrant consideration.

One explanation is the task complexity. Lane's modified Fitts' Law task required movement along all 3 of the robot tool-tip's translational axes, where the present work only considered a 2 DOF task. Additionally, in this study, the subjects knew where the targets were for the duration of the task. Several subjects would begin moving the commanded robot to the next target before delayed video feedback indicated a target hit. In Lane's Fitts' Law study, only one target was in a fixed location; the simulation generated a new target at a random location after each contact with the fixed target. The subjects' knowledge of the target location very likely allowed subjects to shave extra seconds off their completion times.

5 Conclusions and Future Work

This primary goal of this research was to extend the commanded display to a real robotic system. First demonstrated as a realtime teleoperation tool by Lane, the commanded display had been shown to effectively reduce task completion time for a purely simulated system. Experimental testing with the NBV-I manipulator demonstrated the effectiveness of the commanded display on a real-world system, and confirmed Lane's findings. The commanded display nearly eliminated the negative effects of time delay for a robot positioning task.

The study presented here considered a commanded display overlay in a visualization that was independent of the actual camera views. This required the operator to scan between views on the screen. Future study should explore the use of a commanded display overlay on video, similar to many previous predictor systems. With a video overlay, the operator would not have to continually scan between different areas on the screen to obtain the information provided by both the visualizer and video sources. However, the visualizer does have value in offering views that would otherwise be unattainable, and could allow an operator move the viewpoint as the situation required. This is especially useful when the number of camera views is limited due to bandwidth constraints.

Future research should compare the commanded dis-

play with predictive displays. Lane demonstrated the superiority of a commanded display over a basic predictive system for positioning tasks, however more sophisticated predictive displays may offer benefits by simulating dynamic effects. This may prove more suitable for contact operations, especially in conjunction with force feedback. Work should be done to combine commanded and predictive displays. This may be done in a single display, in which the operator can switch between each method depending on which is most suitable for the current task. A hybrid commanded-predictive display may also be devised, in which a commanded simulation generates commands for both the actual and predictive system, preventing the predictor from suffering a drift in calibration.

6 Acknowledgments

The authors wish to thank the NASA Satellite Servicing Capabilities Office at Goddard Spaceflight Center for providing the financial support for this research.

The authors would also like to thank Nicholas D'Amore for supporting the integration of the visualization software with the NBV-I arm DMU software. Thanks are also given to Daniel Goodley, Michael Schaffer, and Erick Arce for assisting with the test setup.

References

- [1] Backes, P.G., "Supervised Autonomy for Space Telerobotics." Jet Propulsion Laboratory, CA, (1993).
- [2] Conway, L., Volz, R., Walker, M., "Tele-Autonomous Systems: Methods and Architectures for Intermingling Autonomous and Telerobotic Technology", *Proceedings of the IEEE International Conference on Robotics and Automation*, 4:1121-1130 (1987)
- [3] Davis, K.P., "Human Factors Evaluation of Operator Interfaces for Teleoperation of a Dexterous Manipulator," M.S. Thesis, University of Maryland, (2014).
- [4] Imaida, T. Yokokohji, Y., Doi, T., Oda, M., Yoshikawa, T., "Ground-Space Bilateral Teleoperation of ETS-VII Robot Arm by Direct Bilateral Coupling Under 7-s Time Delay Conditions," *IEEE Transactions on Robotics and Automation*, vol.20, no.3, 2004, pp499-511.
- [5] Ferrell, W.R., Sheridan, T.B., "Remote Manipulation with Transmission Delay," *IEEE Transactions on Human Factors in Electronics*, 6, 2529 (1965)
- [6] Fitts, P. M., "The information capacity of the human motor system in controlling the amplitude of movement," *Journal of Experimental Psychology*, 47, 381391 (1954).

- [7] Held, R., Efstathiou, A., Greene, M., "Adaptation to Displaced and Delayed Visual Feedback from the Hand," *Journal of Experimental Psychology* vol. 2, no. 6, 1966, pp 887-891.
- [8] Lane, J.C., "Human Factors Optimization of Virtual Environment Attributes for a Space Telerobotic Control Station," Ph.D. Thesis, University of Maryland, MD (2000).
- [9] Lane, J.C., Carignan, C.R. , Akin, D.L., "Advanced Operator Interface Design for Complex Space Telerobots," *Autonomous Robots* **11**, 1:49-58 (2001).
- [10] Ferrel, W.R., Sheridan, T.B., "Remote Manipulation with Transmission Delay," *IEEE Transactions on Human Factors in Electronics*, 6, 2529 (1965)
- [11] Funda, J., "Human Factors Optimization of Virtual Environment Attributes for a Space Telerobotic Control Station," Ph.D. Thesis, University of Pennsylvania, PA (1991).
- [12] Mar, L.E., "Human Control Performance in Operation of a Time-Delayed Master-Slave Telemanipulator." M.S. Thesis, MIT, MA (1985).
- [13] Noyes, M., "Superposition of graphics on low bit rate video as an Aid in Teleoperation." M.S. Thesis, MIT, MA (1982).
- [14] Sheridan, T.B, Ferrel, W.R., "Remote Manipulative Control with Transmission Delay," *IEEE Transactions on Human Factors in Electronics*, 6, 2432 (1963)
- [15] Sheridan, T.B., "Telerobotics, Automation, and Human Supervisory Control." Cambridge: MIT Press, 1992.
- [16] Sheridan, T.B., "Space Teleoperation Through Time Delay: Review and Prognosis," *IEEE Transactions on Robotics and Automation*, vol 9, no. 5, 1993, pp 592-606.