Enhanced Lighting Techniques and Augmented Reality to Improve Human Task Performance

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INTRODUCTION

One of the most versatile tools designed for use on the International Space Station (ISS) is the Special Purpose Dexterous Manipulator (SPDM) robot. Operators for this system are trained at NASA Johnson Space Center (JSC) using a robotic simulator, the Dexterous Manipulator Trainer (DMT), which performs most SPDM functions under normal static Earth gravitational forces. The SPDM is controlled from a standard Robotic Workstation. A key feature of the SPDM and DMT is the Force/Moment Accommodation (FMA) system, which limits the contact forces and moments acting on the robot components, on its payload – an Orbital Replaceable Unit (ORU), and on the receptacle for the ORU. The FMA system helps to automatically alleviate any binding of the ORU as it is inserted or withdrawn from a receptacle, but it is limited in its correction capability. A successful ORU insertion generally requires that the reference axes of the ORU and receptacle be aligned to within approximately 0.25 inch and 0.5 degree of nominal values. The only guides available for the operator to achieve these alignment tolerances are views from any available video cameras. No special registration markings are provided on the ORU or receptacle, so the operator must use their intrinsic features in the video display to perform the pre-insertion alignment task. Since optimum camera views may not be available, and dynamic orbital lighting conditions may limit viewing periods, long times are anticipated for performing some ORU insertion or extraction operations. This study explored the feasibility of using augmented reality (AR) to assist with SPDM operations. Geometric graphical symbols were overlaid on the end effector (EE) camera view to afford cues to assist the operator in attaining adequate pre-insertion ORU alignment.

METHOD

Participants

Twelve participants were recruited from the pool of certified robotic operators available at JSC. These subjects ranged widely in their experience on robotic systems. Some were relatively new employees who had recently completed training working with one of the robotic systems used on ISS. Others included JSC robotic system instructors with experience training astronauts to use the Space Shuttle and/or ISS robotic arm. All participants were familiar with Robotic Workstation controls and procedures.

Experimental Design

The experiment was a classical “mixed” factors design having one factor (order of presentation of treatments) between subjects and one factor (treatment type – overlay or no overlay) repeated within subjects. Each subject performed a total of eight trials, which were divided into two sets of four trials each. One set was performed without overlays, and the other with AR graphical overlays. Half of the subjects experienced a set of four trials with overlays (OV) followed by a set of four trials without overlays (NO). The balance of the subjects experienced the same sets in reverse order.

All trials involved maneuvering the ORU from a predetermined starting position toward the same receptacle. The same set of four different starting positions was used in the same order for the trial groups under the two treatments. Starting positions for the trials were selected to produce the same minimum time for completion (as determined by mechanical characteristics of the DMT). The objective dependent measures for this study are related to the ORU position/orientation at the pre-insertion position above the destination receptacle. These four measures included (1) roll alignment error (degrees) about the X-axis, (2) composite pitch/yaw alignment error (degrees), (3) translation alignment error in the YZ plane (inches), and (4) elapsed time to trial completion (seconds). Coordinate conventions for the experiment are described below. In addition to the objective data collected, subjective evaluations of experimental treatments and methods were gathered by means of a written questionnaire provided to each subject following the completion of the trials. Subjects were encouraged to record any comments regarding the experiment on the questionnaire.

Data analysis including analysis of variance (ANOVA) and post hoc testing of means was performed for all the significant dependent variables. Means comparisons were performed using contrasts in order to circumvent assumptions of homogeneity of variances among sample populations when necessary (Maxwell & Delaney, pp. 145-150).

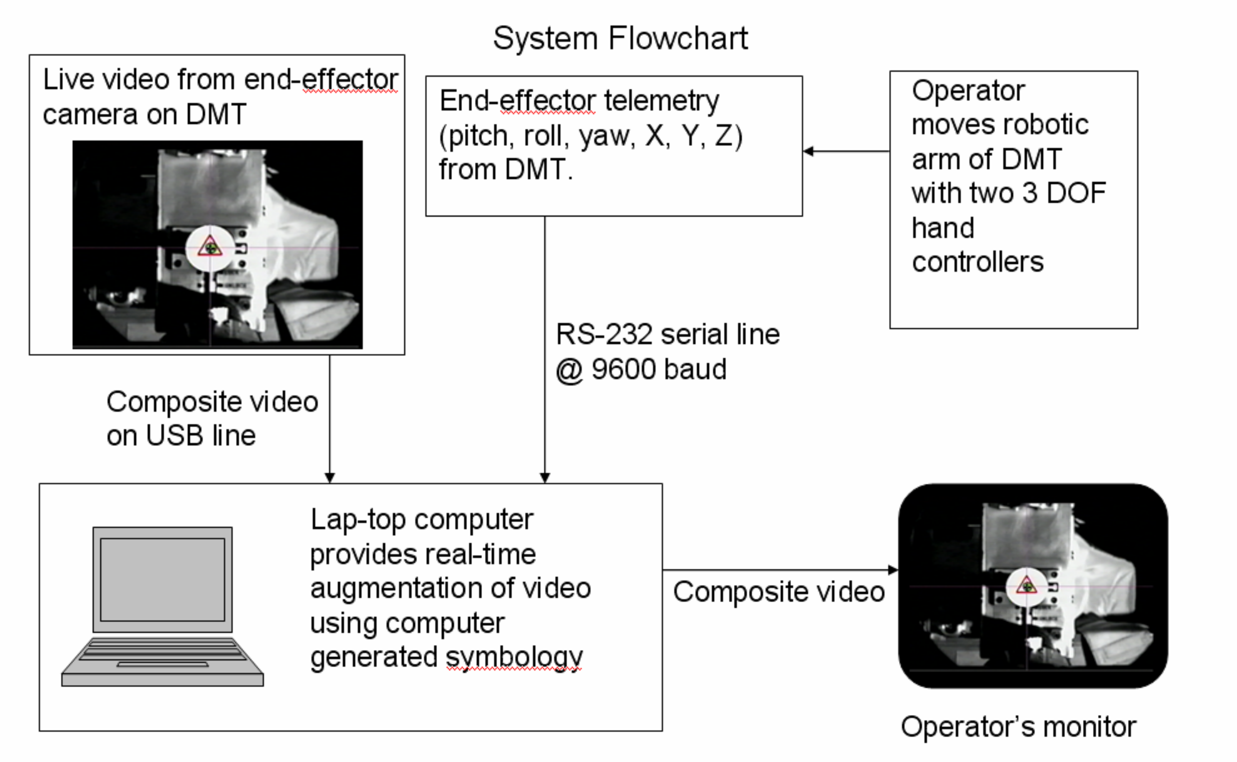
EXPERIMENTAL CONDITIONS

Apparatus

Experimental trials were conducted using a single arm of the DMT and the cupola mockup in the JSC Multiuse Remote Manipulator Facility. Subjects operated the DMT using the Robotic Workstation in the cupola mockup (Figure 1) under the local supervision of the experiment administrator. A trained operator at the DMT console set up initial conditions for each trial and continually monitored operations.

Figure 1. Robotic Workstation in Cupola Mockup

The video signal from the DMT EE camera was routed through the video board in a personal computer (PC) on its way to the EE monitors in the cupola and at the DMT console. DMT telemetry data was also made available to the PC serial port from the DMT console. Custom software was developed to use the telemetry data to superimpose the overlays over the EE video signal presented to the monitors as required for the trial conditions. This software was developed using the open-source "ARToolKit" library (University of Washington Human Interface Technology Laboratory) to produce and manipulate the overlay graphics.



DMT Augmented Reality System Flow Chart.

The ORU used for the experiment was the Remote Power Control Module (RPCM) mockup. Figure 2 shows the RPCM mockup above the open receptacle into which it was to be inserted. This payload was grappled by a Robotic Micro-conical Tool (RMCT), which was installed in the EE gripper of the DMT by the DMT console operator prior to the trials. Subjects were not required to grapple the ORU for this experiment.

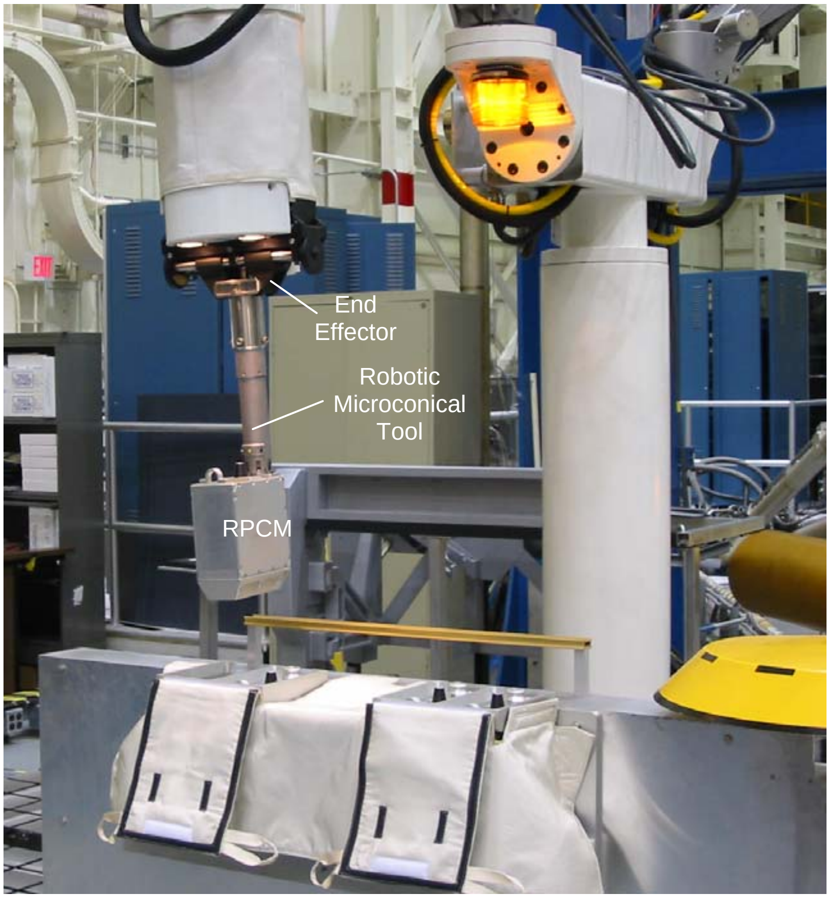


Figure 2. DMT Positioning RPCM Over its Receptacle

Four cameras and a flood lamp were arrayed around the ORU receptacles, as shown in Figure 3. The flood lamp provided adverse, oblique lighting on the payload and the ORU receptacles to simulate stark, sunlit orbital lighting conditions. The cameras were mounted on pan/tilt units at different heights. The Robotic Workstation provided three monitors to accommodate views from any of these cameras and the EE camera, as shown in Figure 1.

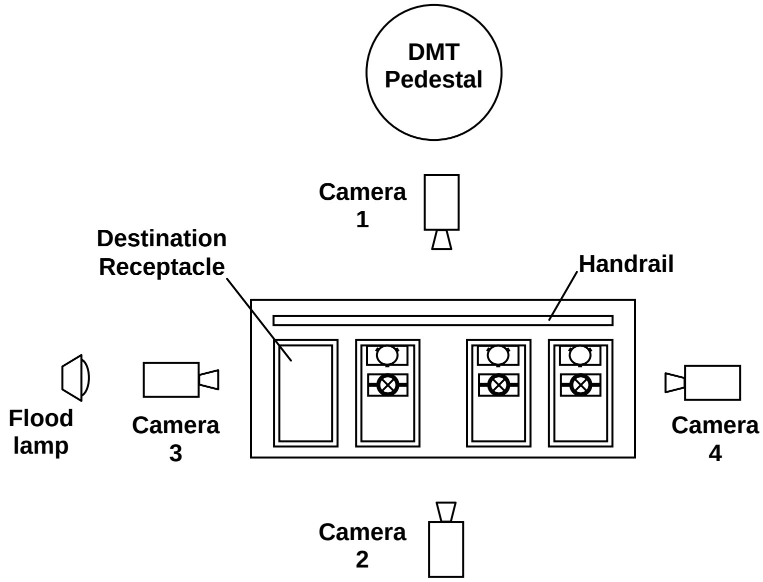


Figure 3. Camera and Flood Lamp Arrangement

Coordinate Conventions

Since the AR overlays appear only in the EE camera view (Figure 4), the operator can adopt an "internal" or "inside-out" (Huchingson, 1981) frame of reference and "fly" the grappled ORU using a right-handed set of orthogonal coordinates mapped to the EE camera monitor. Translations and rotations are referred to the monitor's "vertical", "horizontal", and "in/out" axes. The in/out axis is called the X-axis, with the positive direction into the monitor screen. The horizontal axis is termed the Y-axis, with the positive direction toward the right of the screen. The remaining, vertical axis is called the Z-axis, which has its positive direction downward on the monitor. Rotations are referred about these orthogonal axes. A positive, right-handed rotation about the X-axis of the Robotic Workstation joystick, results in an ORU "rolling" motion to the right. A positive, "pitch-up" rotation of the joystick about the Y-axis, results in an upwardly tilting change in the EE monitor view. A positive "yaw-right" rotation of the joystick about the vertical Z-axis causes the EE monitor view to pan to the right. The origin for the axes is the "point of reference" (POR) for the EE/ORU, where the axis of the RMCT exits the "back" (connector) side of the ORU. The ORU rotational motions occur about the POR, and since the grapple target/camera axis is offset from the RMCT axis, there is a parallax consideration introduced.

Description of the AR Overlays

The system of AR symbol overlays described here was developed to speed the process of maneuvering a grappled ORU among bays where they may be stowed or operated. The intentions underlying the overlay designs were (1) to provide guidance to the intended (perhaps distant) destination for the RPCM ORU being transported and (2) to assist the operator to avoid confounding the needs for rotation or translation inputs from the Robotic Workstation hand controllers. Most of the symbols used in the overlays were arranged for enhanced situational awareness however the roll arrow provided a direct recommendation for operator action. In heads-up display parlance, these methods are respectively referred to as "situation guidance" and "command guidance" (Foyle et al., 2002).

Subjects using the overlays were urged to use available camera views in addition to the EE camera view to maintain overall situational awareness. Subjects were also urged to adopt an internal frame of reference as they maneuvered the RPCM to the destination receptacle while referring to the EE view. As shown in Figure 4, much of the EE camera view was occupied by the grappled ORU, and overlay symbols were superimposed over the image of the RPCM. Since the overlays were registered with the EE during RPCM insertion, the overlays remain aligned with the RPCM features within the EE camera view. The (modified truncated cone) grapple target appeared centered in the EE camera view. In the case of the relatively small RPCM ORU, some of the background beyond the grappled ORU was in focus at the lateral margins of the EE camera view.

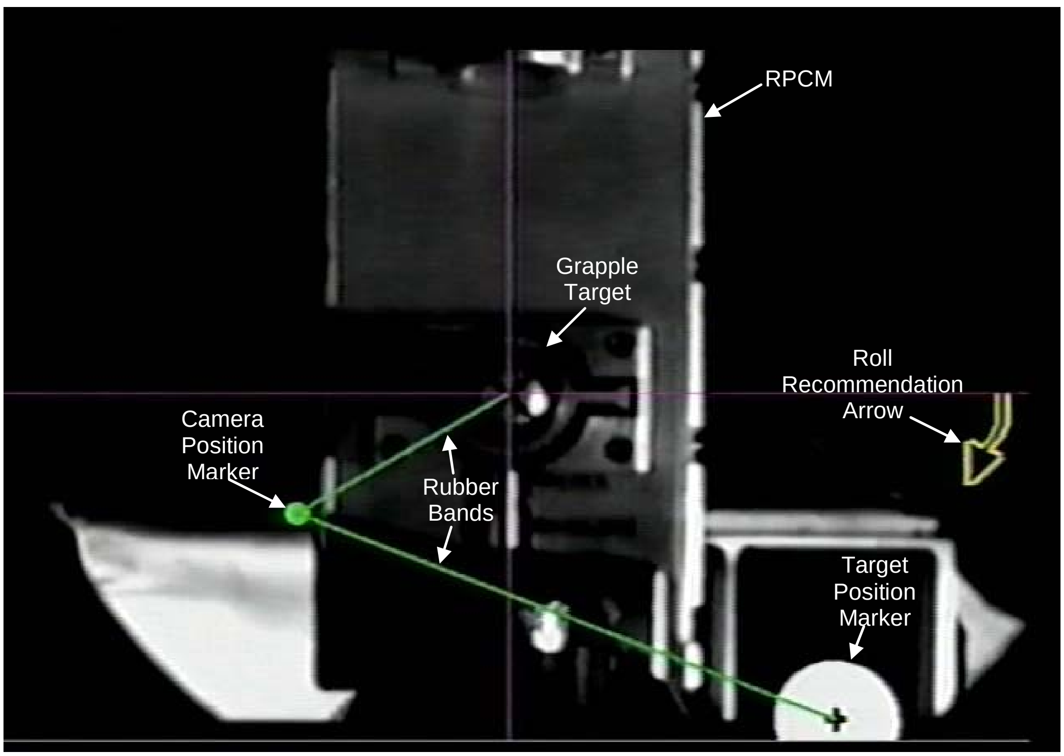


Figure 4. Overlay Symbols During Initial Stages of Alignment

Figure 4 illustrates the overlay symbols likely to be encountered during the early stages of an ORU maneuver. The camera aiming point is marked by the intersection of the vertical and horizontal magenta lines at the center of the EE camera view. This point coincides with the center of the truncated cone target (diagonal cross) used to grapple the RPCM. The magenta lines remain superimposed on the field of view at all times, but they are "overwritten" by any other coincident overlay symbols.

Roll (rotation about the X-axis)
If alignment of the RPCM and the destination receptacle requires rotation of the RPCM about the X-axis, a curved roll recommendation arrow appears, originating on the +Y axis (magenta center line) and pointing in the direction to correct the roll alignment error (Figure 4). The length of the arrow indicates the magnitude of the error. A left roll recommendation is indicated by an arrow curving to the left above the +Y axis, while a right roll recommendation (Figure 4) is indicated by an arrow curving to the left below the +Y axis. When the roll alignment error has been minimized within the allowable tolerance, the roll arrow vanishes altogether. It should be observed that roll motions are about the centerline of the grapple fixture, which is shown at the lower edge (extreme +Z direction) of the EE monitor display – not about the camera aiming point. The offset between the grapple fixture and the grapple target leads to a preferred order of operations in aligning the RPCM with the destination receptacle, as described below.

Rotation about the Y-axis and Z-axis
Extending outward from the central camera aiming point is a green “rotation rubber band” line, which terminates at the center of the circular camera position marker. If the camera position marker is not within the field of view of the EE camera, the rubber band extends in the direction of the camera position marker to the edge of the monitor display field.

The camera position marker (Figure 4) projects the location of a point in the Y-Z plane just outside the destination receptacle for the RPCM. The center of the circle marks the point in this Y-Z plane that lies in the +X direction from the camera lens. If the camera’s position marker coincides with its aiming point, the axis of the camera (and hence the longitudinal axis of the RPCM) is parallel to the X-axis of the receptacle. *The position of the camera aiming point relative to the camera position marker depends only on pitch and yaw inputs from the rotation (right) hand controller “stick”.* Pitching forward with the hand controller moves the camera aiming point down relative to the camera position marker in the monitor view (*i.e.*, in the +Z direction). Yawing to the right with the hand controller moves the camera aiming point to the right relative to the camera position marker (*i.e.*, in the +Y direction). The rotation rubber band thus shortens or lengthens in accord with the pitch/yaw error of the camera. Translation inputs from the left (knob) hand controller do not affect the position of the camera aiming point relative to the camera position marker.

Translation in the Y or Z direction
A second green line, the translation rubber band, extends outward from the camera position marker to the center of the target location marker. The target location marker is a relatively large white circle, whose center is marked by a black cross (Figure 4). Optimum alignment of the RPCM for insertion into the receptacle at the target location occurs when the camera position marker and camera aiming point both coincide with the target location marker. The position of the camera position marker relative to the target location marker is governed by translation hand controller (knob) commands using the left hand. As the translation error between the camera and target positions decreases, the translation rubber band shortens accordingly. *The position of the camera aiming point relative to the target location marker depends not only on pitch and yaw inputs from the rotation (right) hand controller “stick”, but also on inputs from the translation (left) hand controller “knob”.*

A proximity warning is provided to advise the operator to enable the Force/Moment Accommodation (FMA) system prior to maneuvering the RPCM closer to the receptacle in the +X direction. FMA protects both the RPCM and the receptacle hardware from inadvertent collision damage. The warning symbol consists of a red triangle at the center of the EE monitor display. Figure 5 shows the nominal indications just prior to enabling FMA and beginning insertion with a +X translation command.

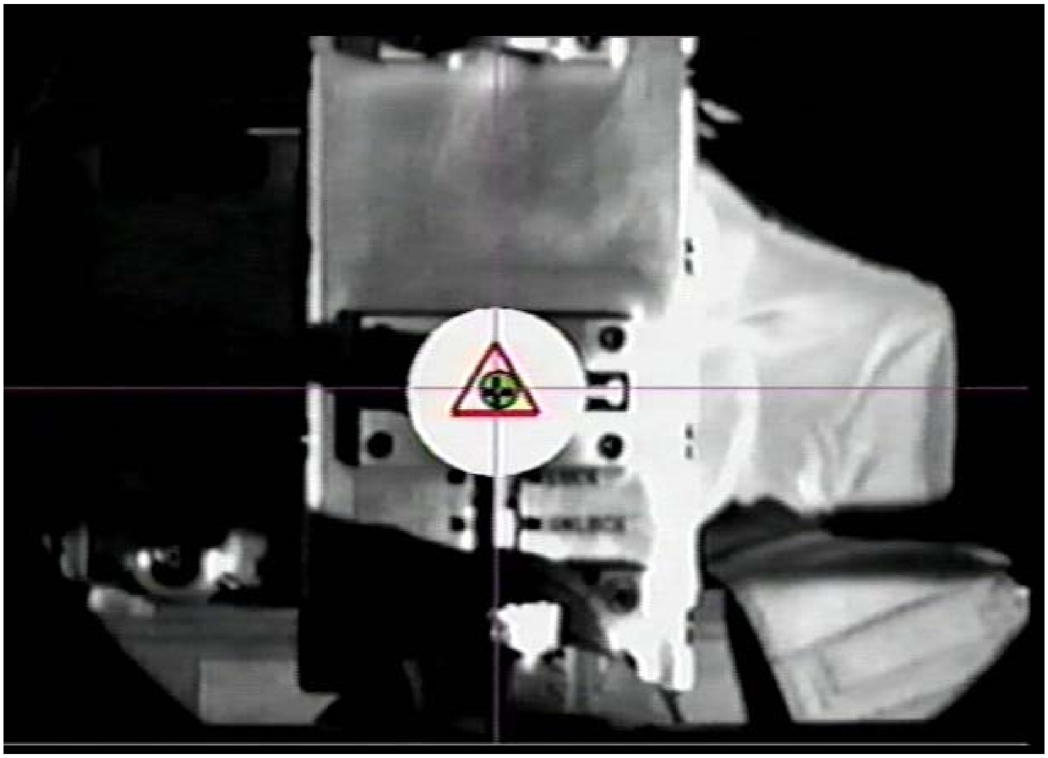


Figure 5. Overlay Appearance with ORU in Position for Insertion

Symbol features
Colors for symbol elements were not selected according to any coding requirements for orbital robotic operations. The rubber band lines and the center of the camera position marker were made green to avoid any confusion with yellow cautionary or red warning symbols in the Robotic Workstation display repertoire. Both the camera position marker and the white target marker symbol were outlined in black to afford high contrast against light backgrounds. Since the roll recommendation arrow by itself is indicative of one component of alignment error, it was made yellow to advise caution. The triangle of the proximity warning indicator was made red, because it is indicative of a potential collision hazard and warns the operator to engage the FMA system.

Elements of the symbols were projected at different “levels” in the display in order to avoid obscuring critical features in one symbol with features of another. At the lowest level was the white circle of the target position marker. The next level contained the magenta lines marking the center of the camera view. Above this level came the camera position marker, followed by the target position marker's central black cross. The rubber band lines and the roll recommendation arrow occupied the uppermost level.

Optimized Procedure Using Overlays
The design of the overlay system suggests an optimized procedure for pre-insertion ORU maneuvering, which may simplify task completion by minimizing uncertainty in selecting whether rotation or translation hand controller inputs are appropriate to reduce alignment error. This feature is most advantageous when the ORU is nearly correctly aligned with the receptacle, since the need for small rotation or translation corrections may be difficult to discern from cues in the non-augmented camera views. Since the ORU rotates and translates relative to the point where the EE rotation axis intersects the far (connector) surface of the ORU, and the target and camera aiming point are offset from this point, there is asymmetry in the interactions of the control commands. If the camera aiming point is moved to coincide with the target location marker without first minimizing the residual rotation error, subsequent rotations will introduce additional translation error. The resulting uncertainty may lead to time-consuming trial and error experimental control inputs. The following procedure was demonstrated for all the subjects during their overlay familiarization sessions.

Step 1. Prior to maneuvering the ORU using the Robotic Workstation hand controls, the operator was urged to make use of the available camera views to ensure that no obstacles lay in the intended path of motion for the DMT or the grappled ORU. It was suggested that if possible, an overview of the starting and intended destination positions of ORU should be maintained on the Robotic Workstation monitors.

Step 2. In order to prevent possible disorientation and to promote efficient mapping of the hand controller motions to the ORU environment, it was recommended that the error in roll orientation be minimized by commanding a compensating roll with the rotation hand controller in accordance with the roll recommendation arrow early in the maneuvering process. Once the roll recommendation arrow disappeared, indicating that the error was minimal, it was suggested that the performance of other maneuvers should be more easily coordinated.

Step 3. The next stage in the optimized alignment process involved primarily the use of the rotation (right) hand controller – pitching and yawing the camera along the path of the rotation rubber band in the direction of the camera position. Once the EE camera aiming point coincides with the camera position marker, the EE/ORU X-axis parallels the X-axis of the destination receptacle, and rotation errors are minimal.

Step 4. Once the rotation error is minimized, the EE camera aiming point may be translated in the direction of the translation rubber band toward the target location marker. Translation commands from the left hand controller should not disturb the rotational alignment of the EE relative to the camera position marker. When the camera aiming point coincides with both the camera position marker and the target location marker, the ORU should be nearly oriented for insertion in the receptacle using +X translation hand controller inputs.

Some more experienced Robotic Workstation operators felt confident in making simultaneous rotation and translation corrections (especially early) during maneuvering. The subjects preferring to use coordinated simultaneous hand controller inputs were shown that overlays did not interfere with this method, but it was explained that the operator should give rotation corrections higher priority because of the parallax between the camera and the EE rotation axis.

It was also explained that error minimizations giving translation corrections priority over rotation corrections may be used successfully in a converging iterative process to achieve the insertion position. This is less efficient than giving higher priority to rotation operations, which requires only a single iteration.

The same correction prioritization (roll, rotation, then translation) is advantageous for alignment of the ORU without overlays. Initial roll correction reduces the operator's cognitive load by reducing interaction between Y-axis and Z-axis rotations or translations. Large initial alignment errors may be reduced more quickly by applying rotational corrections about the Y-axis and Z-axis before translating in the Y or Z directions.

EXPERIMENTAL PROCEDURE

Preliminary Equipment Setup

The operation of the DMT, all video cameras, the flood lamp, and Robotic Workstation equipment in the cupola was verified prior to the subject's arrival. In addition, the overlay registration relative to the EE camera view was checked with the RPCM in the pre-insertion position. This was accomplished by the DMT console operator, who first maneuvered the RPCM to the anticipated pre-insertion position using the overlays as a guide. The operator then enabled the FMA feature of the DMT software and attempted to insert the RPCM into the receptacle using a pure +X translation only. The RPCM was fully inserted and adjusted to the most centered, neutral position. No adjustment was needed if the overlay graphics were properly aligned. The RPCM was then withdrawn from the receptacle by means of a pure –X translation to the pre-insertion position. The graphics alignment was again confirmed at this point, making allowances for any small offsets introduced by FMA operation. If there were any significant discrepancies between the RPCM and the AR overlays at the pre-insertion position, the AR graphics position, orientation, and roll reference values in the overlay generation software were corrected accordingly. If adjustments were made, the procedure outlined above was repeated.

Preliminary Subject Activities

Each subject was provided with a printed layman's description of the experiment, and the main features included in this summary were reviewed by the experiment administrator. Any technical or procedural questions were answered to the subject's satisfaction, and the subject was asked to read and approve the informed consent. If the subject was not familiar with the operation of the DMT, the console operator, a certified robotics operator, provided a brief introductory "walk-through" of the system, explaining any major differences between the DMT operation and the system(s) familiar to the subject. Following this introduction, the subject was conducted to the cupola for further familiarization and the actual trials.

Overlay Familiarization

At the beginning of the experiment session, the subject was introduced to the best use of the AR overlays. The experiment administrator explained the functions of the overlay features using a demonstration ORU starting position. The hand controllers were placed in "vernier" mode, and the subject operated the DMT using the Robotic Workstation and the overlays to move the RPCM to the pre-insertion position. Once the subject had attempted an insertion using the overlays, she/he was presented with a different practice starting position and allowed to attempt a self-paced alignment/insertion. Throughout the demonstration and practice trials, the administrator offered advice and answered any questions the subject posed concerning the use of the overlays. Following the practice trial, the subject was asked whether he/she felt competent to use the overlays to perform a series of trials. If the subject felt the need for additional practice, more practice was provided. If the subject expressed confidence in her/his ability to use the overlays, the test conductor requested that the ORU be positioned for the first trial. During the ORU setup time for the first trial, the subject was reminded that the eight trials would be self-paced, and that he/she could take breaks as required. The subject was also informed that the trials would consist of two groups of four having the same treatment (overlays or no overlays), and the order of the treatments was revealed. The subject was urged to use the available camera views to maintain overall situational awareness during all the trials. The subject was also reminded of the non-competitive nature of the trials and analysis methods, with encouragement to perform the task as quickly and accurately as possible. No emphasis was placed on limiting rates of application or on the coordination of multiple control degrees of freedom. The subject was urged to adjust her/his chair for the most comfort in operating the Robotic Workstation controls. When the console operator had placed the ORU in the starting position for the trial, data recording was initiated, and control was transferred from the DMT console to the subject's Robotic Workstation. The subject was then ready to begin Trial 1. The DMT's FMA feature was made inactive for the initial portion of each trial.

Experimental Trial Activities

The first action performed by the subject during a trial with or without overlays was typically to locate the ORU in at least one auxiliary camera view. The subject then proceeded to maneuver the ORU into the pre-insertion position outside the receptacle. When the pre-insertion position had been attained, the subject released the Robotic Workstation controls and requested that the console operator enable the Force/Moment Accommodation (FMA) system in preparation for insertion. After receiving assurances that FMA was active, the subject attempted to insert the ORU into the receptacle using +X commands from the translation hand controller. Once the ORU had stopped moving in response to the +X command, the subject released the controls, and the test conductor requested that the console operator withdraw the ORU and move it to the starting position for the next trial.

DATA ANALYSIS

Objective Data Recording

Data for the experiment were extracted from the multitude of records accumulated by the DMT system during the trials. The sampling interval for recording was set to 100 milliseconds. The records used tracked position and orientation relative to the center of rotation of the ORU, the Point-Of-Reference (POR). This point resides along the axis of the RMCT at the surface opposite the grapple fixture on the ORU. DMC terms for the roll, YZ position, and pitch/yaw variables are identified with the "*PORact _*" prefix. Reference values for roll, pitch, yaw, Y position and Z position were determined from values recorded during the preliminary overlay alignment verification.

Roll Alignment Error
This metric is calculated as the difference (degrees) between the pre-insertion and reference values for the DMT $PORactr$ variable:

$$Error_{roll} = PORactr_{pre-insertion} - PORactr_{reference}$$

Pitch/yaw Alignment Error
This metric is the angle (degrees) between the receptacle (+X) axis and the RPCM axis through its point of reference. If $\theta_{pre} = PORactp_{pre-insertion}$, $\theta_{ref} = PORactp_{reference}$, $\phi_{pre} = PORactw_{pre-insertion}$, and $\phi_{ref} = PORactw_{reference}$, the pitch/yaw error is

$$Error_{pitch/yaw} = \cos^{-1}\left(\cos\theta_{pre}\sin\phi_{pre}\cos\theta_{ref}\sin\phi_{ref} + \cos\theta_{pre}\cos\phi_{pre}\cos\theta_{ref}\cos\phi_{ref} + \sin\theta_{pre}\sin\theta_{ref}\right)$$

YZ Alignment Error
This measure is the two-dimensional difference (inches) between the pre-insertion and reference positions in the YZ plane. The DMT variables $PORacty$ and $PORactz$ record these positions for the reference and trial samples.

$$Error_{YZ} = \sqrt{\left(PORacty_{pre-insertion} - PORacty_{reference}\right)^2 + \left(PORactz_{pre-insertion} - PORactz_{reference}\right)^2}$$

Time to Completion
Time to completion for a trial includes the interval (seconds) during which the subject exerts control over the DMT and cameras prior to insertion. The interval begins when the subject initially adjusts the camera controls or moves the hand controllers, whichever occurs first. The interval ends when the subject releases the hand controllers prior to requesting that FMA be enabled for insertion of the RPCM.

RESULTS

Performance on the alignment tasks described above was examined using analysis of variance and post-hoc mean tests. In all but the XY alignment error comparisons, however, the variances between the no-overlay-then-overlay (NO-OV) order and overlay-then-no-overlay (OV-NO) order subject groups were significantly different, as determined by the test for homogeneity of variance between related samples (Bruning & Kintz, pp. 109-110). For this reason, comparisons between non-overlay and overlay trial means for the other performance metrics used contrast test techniques, which are not sensitive to non-homogeneous variances (Maxwell & Delaney, pp. 144-150).

Roll alignment error

Table 2 shows the analysis of variance for roll alignment error. Variances of the four-trial mean errors were significantly different for the two order groupings of subjects ($p < 0.012$), so a comparison of means for the treatments was accomplished using a contrast test. This test indicated that the mean roll alignment error using the overlays was significantly ($p < 0.02$) lower than the mean error without overlays, as shown in Figure 7.

Source	SS	df	MS	F	P
Total	3.38131606	23			
Between S	0.84484965	11			
Order	7.3151E-06	1	7.3151E-06	8.6585E-05	0.9928
Error: S w/in Order	0.84484234	10	0.08448423		
Within S	2.53646641	12			
Treatment (Trt)	1.56608732	1	1.56608732	16.1402	0.0024*
Trt x Order Interaction	7.4378E-05	1	7.4378E-05	7.6654E-04	0.9785
Error: Trt x S(Order)	0.97030471	10	0.09703047		

*significant at α = 0.05 level

Table 2. Analysis of Variance for Roll Alignment Error

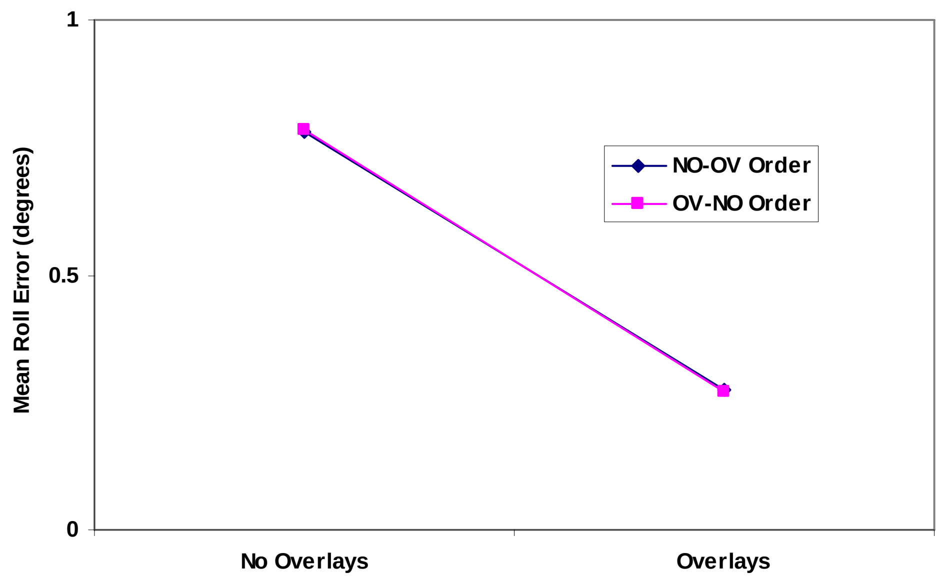


Figure 7. Means Comparison for Roll Alignment Error

Pitch/yaw Alignment Error

The analysis of variance for pitch/yaw alignment error is shown in Table 3. Variances of the four-trial mean errors were significantly ($p < 0.014$) different for the two order groupings of subjects, so a comparison of means for the treatments was accomplished using a contrast test. The contrast test revealed that the mean pitch/yaw alignment error using the overlays was significantly ($p < 0.0103$) lower than the mean error without overlays, as illustrated in Figure 8. The apparent interaction between trial order and treatment was not significant at the $\alpha = 0.05$ level.

Source	SS	df	MS	F	P
Total	6.14366655	23			
Between S	0.8795165	11			
Order	0.01903151	1	0.01903151	0.2212	0.6482
Error: S w/in Order	0.86048499	10	0.0860485		
Within S	5.26415005	12			
Treatment (Trt)	4.20526529	1	4.20526529	50.505	< 0.0001*
Trt x Order Interaction	0.22624114	1	0.22624114	2.7171	0.1303
Error: Trt x S(Order)	0.83264362	10	0.08326436		

*significant at $\alpha = 0.05$ level

Table 3. Analysis of Variance for Pitch/yaw Alignment Error

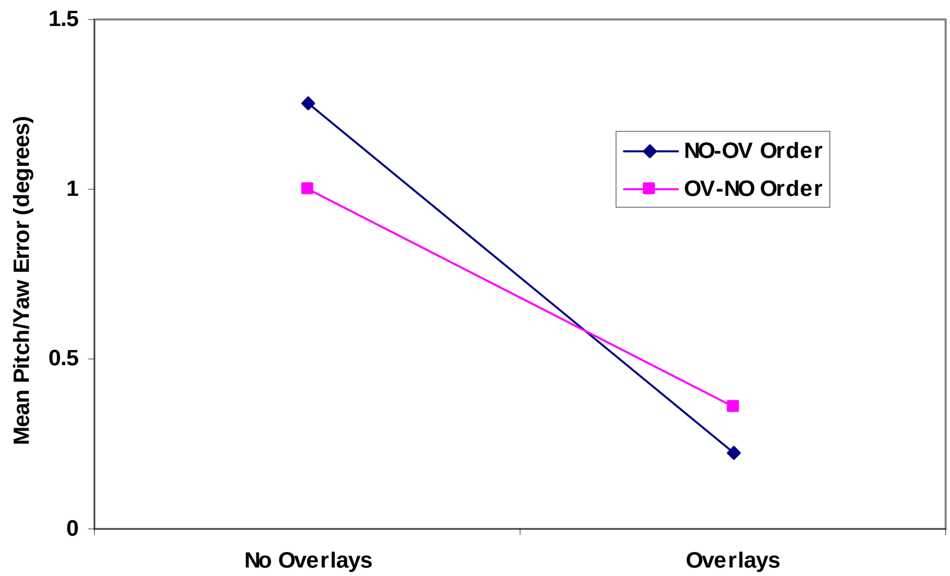


Figure 8. Means Comparison for Pitch/yaw Alignment Error

YZ Alignment Error

Results of analysis of variance for mean YZ alignment errors are shown in Table 1. Variances of the four-trial mean errors were not significantly different for the two order groupings of subjects ($p > 0.98$), so a comparison of means for the treatments was accomplished using a standard t-test. The mean YZ alignment error using the overlays was significantly ($p < 0.011$) lower than the mean error without overlays, as shown in Figure 6.

Source	SS	df	MS	F	P
Total	0.5661955	23			
Between S	0.12289323	11			
Order	0.00039767	1	0.00039767	0.0325	0.8606
Error: S w/in Order	0.12249556	10	0.012249556		
Within S	0.44402631	12			
Treatment (Trt)	0.28938562	1	0.28938562	18.8386	0.0015*
Trt x Order Interaction	0.00102759	1	0.00102759	0.0669	0.8012
Error: Trt x S(Order)	0.1536131	10	0.01536131		

*significant at $\alpha = 0.05$ level

Table 1. Analysis of variance for YZ alignment error

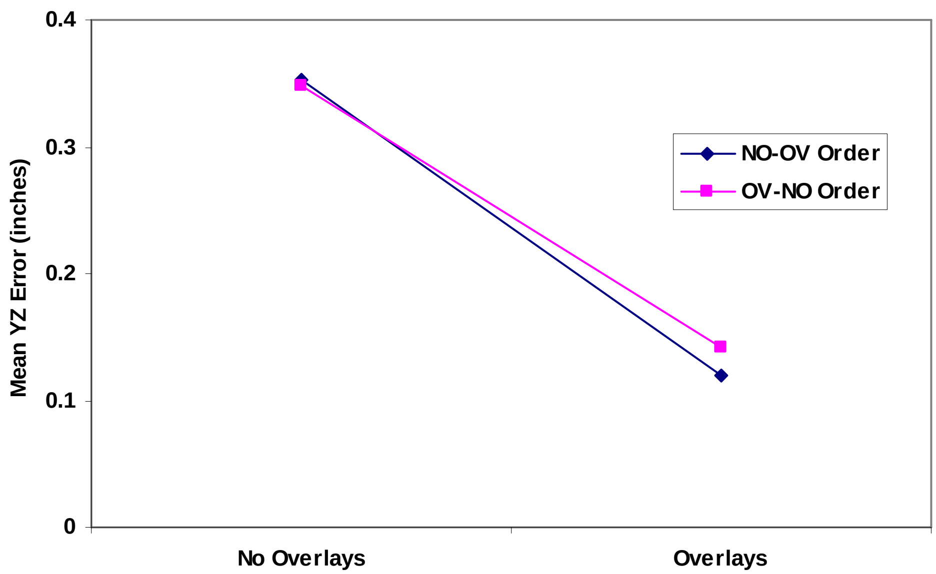


Figure 6. Means Comparison for YZ Alignment Error

Time to Completion
As shown in Table 4, the analysis of variance for time to completion revealed significant interaction between the treatment and order variables ($p < 0.05$). Variances of the four-trial mean times to completion for the two order groupings of subjects were also non-homogeneous at the $p < 0.0001$ level, so a comparison of means for the four treatment-by-order combinations was performed using contrast tests. The results of these tests are shown in Table 5. Whereas the difference in time to completion was significantly less ($p < 0.0359$) with overlays than without overlays in the NO-OV trials, the similar difference for the times to completion in the OV-NO trials was not significant ($p > 0.16$). Some insight into this outcome is provided by examining times to complete individual NO-OV and OV-NO trials in Figure 10 and Figure 11, respectively. The vertical scales in these figures are the same, and the apparent difference between the plots seems to be associated with the performance of subjects S05, S11, and S13 during the first four (NO) trials. S05 required much more time to complete the initial NO trial than any others. Completion times for S13 decreased monotonically through the NO trials, while S11 exhibited more variability, with the third trial requiring more time.

Source	SS	df	MS	F	P
Total	450197.634	23			
Between S	200367.955	11			
Order	6133.28468	1	6133.28468	0.3158	0.5865
Error: S w/in Order	194234.67	10	19423.467		
Within S	249829.679	12			
Treatment (Trt)	137814.721	1	137814.721	19.1227	0.0014*
Trt x Order Interaction	39946.3826	1	39946.3826	5.5428	0.0403*
Error: Trt x S(Order)	72068.5763	10	7206.85763		

*significant at $\alpha = 0.05$ level

Table 4. Analysis of Variance for Time to Completion

Conditions		Numerator	Denominator	F	df	p
NO-OV, NO	**NO-OV, OV**	163077.584	20102.7009	8.1122	5.8616	0.0359*
NO-OV, NO	**OV-NO, NO**	38692.3905	20897.1915	1.8516	6.2761	0.2225
NO-OV, NO	**OV-NO, OV**	101047.305	22623.6453	4.4664	7.1249	0.0724
NO-OV, OV	**OV-NO, NO**	42900.7002	4006.6794	10.7072	9.6051	0.0096*
NO-OV, OV	**OV-NO, OV**	7387.27676	5733.13312	1.2885	8.3692	0.2892
OV-NO, NO	**OV-NO, OV**	14683.5196	6527.6238	2.2494	9.3361	0.1679

*significant at $\alpha = 0.05$ level

Table 5. Means Comparison Tests for Time to Completion

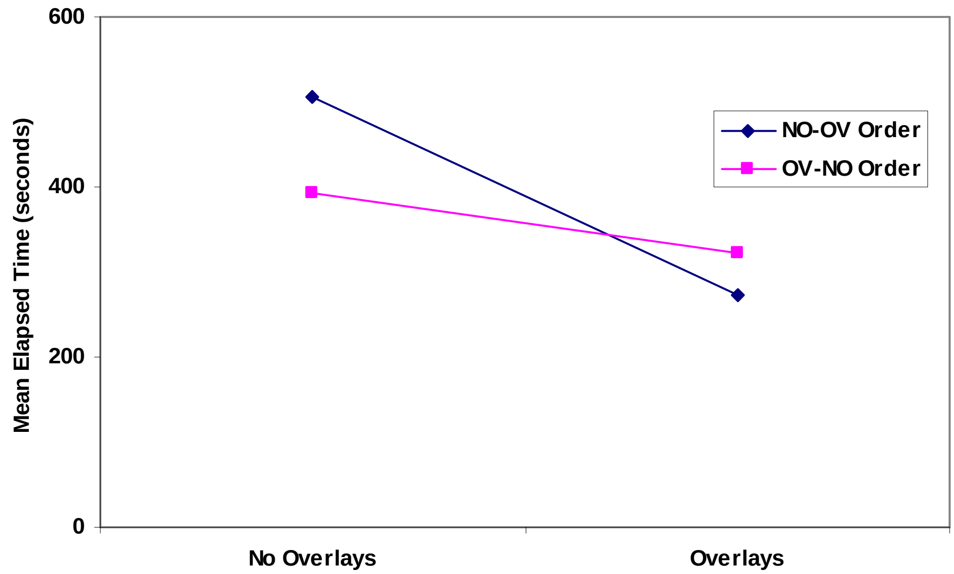


Figure 9. Means Comparison for Time to Completion

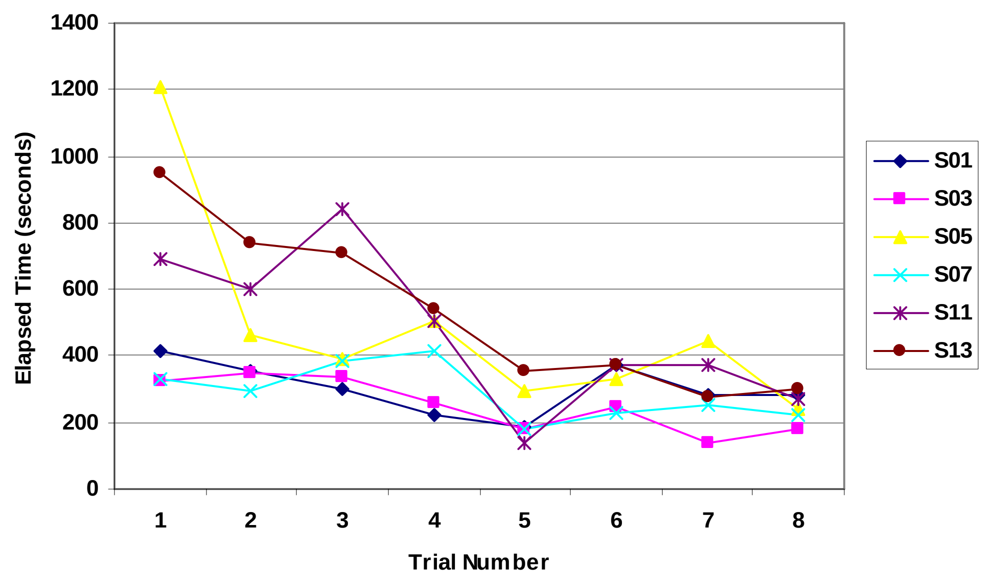


Figure 10. Elapsed Times to Completion for NO-OV Trials

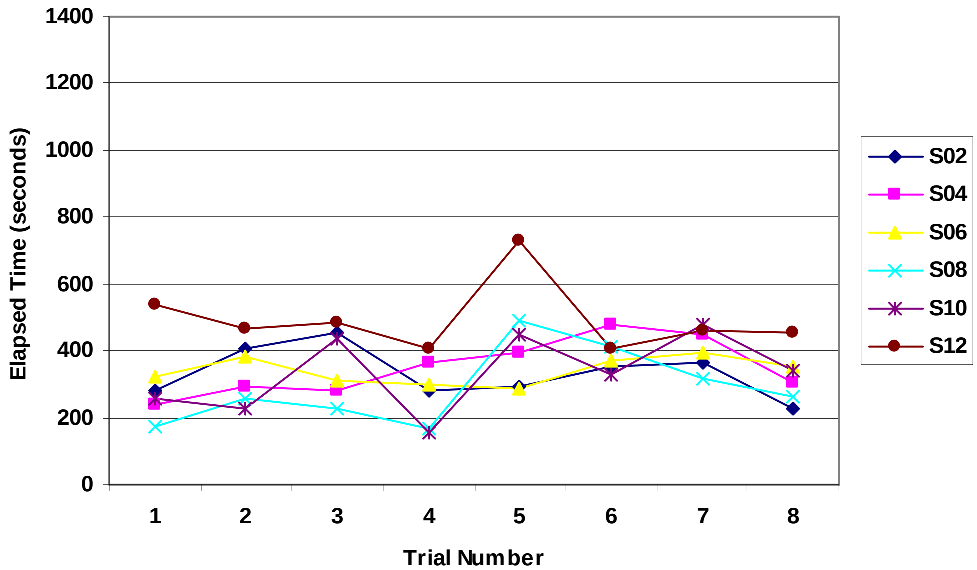


Figure 11. Elapsed Times to Completion for OV-NO Trials

Post-trials Survey

The results of the survey administered following the subject's completion of all eight trial is presented in Table 6. In general, it is apparent that the subjects believed the overlays were helpful.

Statement	Completely Agree	Agree	Neutral	Disagree	Completely Disagree
1) Instructions concerning the use of the overlays were clear.	10	2	0	0	0
2) Adequate practice with the overlays was provided prior to the trials.	10	2	0	0	0
3) Functions of the overlays were easy to understand.	4	8	0	0	0
4) Arrangement of the overlays seemed intuitive.	4	7	1	0	0
5) Overlays were easy to distinguish from their background.	8	3	1	0	0
6) Rubber band features of the overlays clearly indicated required hand controller inputs.	4	6	0	2	0
7) Overlays helped to compensate for adverse lighting conditions.	9	1	2	0	0
8) Overlay information was helpful/useful in performing the ORU alignment operation.	12	0	0	0	0
9) Overlay information did not hinder the completion of the ORU alignment.	12	0	0	0	0
10) The overlays increased confidence in the results of the alignment task.	10	2	0	0	0
11) There were no noticeable differences in task difficulty with or without overlays.	0	0	1	6	4
12) The overlays allowed the speed of alignment to be increased.	10	1	0	1	0
13) The use of overlays interfered with overall situation awareness.	0	1	1	1	9

Table 6. Questionnaire Responses

DISCUSSION

The results of this experiment indicate that overlays improve performance in maneuvering an ORU in preparation for inserting it into a receptacle. Despite the small number of subjects available to participate, three of the four performance metrics showed statistically significant improvements in pre-positioning accuracy using overlays. Trial completion time results are slightly less clear cut, but variability in performance was reduced for all metrics during trials using overlays.

In the cases of all metrics except roll error, there may be evidence of increased performance with practice (Figures 6, 8, and 9). For trials without overlays, the subjects experiencing no overlays in the first four trials showed greater error than did the subjects experiencing no overlays in the last four trials. Similarly, for trials with overlays, the subjects experiencing overlays in the first four trials showed greater error than did the subjects having overlays in the last four trials. Only in the case of pitch/yaw error, however, is the order/treatment interaction significant at the $\alpha = 0.05$ level.

Position Determination Assumptions

A fundamental assumption underlying the use of overlays to improve robotic operations is that the position of the end effector is accurately known. For this investigation, POR location was taken directly from the calculations by the monitoring program running on the DMT console computer. The location was calculated by using known component dimensions and joint angle measurements. The uncertainty in the POR location accumulates with the degrees of freedom available for robotic motions. The DMT location data was checked prior to each trial and proved adequately stable for the purpose of the experiment. In actual operations, however, additional sources for error will likely be encountered in calculating payload position from joint angles and robot arm dimensions. A method of directly estimating the payload position relative to the destination receptacle independent of the robot geometry is essential for practical applications using overlays. This may be provided by an independent position sensing system or, if camera views of the scene are available, through photogrammetric methods. Investigations into the latter are currently underway at JSC in collaboration with Wayne State University.

Subjects

Experience using the Robotic Workstation varied widely among the subjects, and differences in performance were not directly attributable to this factor. If possible, future studies relating to the effectiveness of overlays should balance subject groups according to prior robotic experience. Such studies should be planned to include more subjects. This implies that future work should consider using computer-based simulations or robotic systems other than the DMT, which necessitates specialized training and certification for operators. A larger pool of subjects having a wide range of experience might be used to investigate potential AR applications, such as the use of overlays as a training aid.

Symbol Rationale

The symbol set chosen is intended to provide guidance in cases of extreme misalignment. It is also designed to reduce the likelihood of an operator's confounding rotation and translation cues as the ORU approaches pre-insertion alignment. The inclusion of the camera position marker allows unambiguous, decoupled tracking of rotation and translation by the ORU.

With the exception of the roll recommendation arrow, all symbols afforded the operator situation guidance. Only the roll recommendation arrow provided command guidance, demanding that the operator respond with a particular control input. Since the ORU maneuvering task lends itself to an internal frame of reference, it is conceivable that the roll recommendation arrow might be replaced by a situation guidance symbol, similar to the artificial horizon commonly used in aircraft attitude indicators. Comments by several of the subjects in this study suggested that arrows along the rubber bands might provide helpful prompting for the correct direction of operation for the hand controls. Such a modification of the rubber band lines would essentially convert their mode of operation from offering situation guidance to providing command guidance. The relative merits of the command guidance scheme compared to that of situation guidance in the ORU positioning task affords potential opportunities for future research.

Conclusions and Future Work

This study illustrates some of the potential for the application of AR overlays in robotic control systems. If symbolic AR overlays were included in the operator interface for future robotic operations, such systems might accrue benefits in addition to reduced errors and task time. With appropriate simulation software, the overlays might provide an advantage in training for robotic applications. A simulation having the appropriate fidelity and AR overlays to prompt the correct actions might provide valuable “refresher” training between infrequent actual robotic tasks during extended exploration missions. This hypothesis could be tested within a subject pool on the ground by means of test-retest performance evaluations over varying lengths of time without intervening practice.

The relative merits of overlays providing situational guidance versus their providing command guidance could be studied by means of simulations of moderate fidelity. Any such research should also address the effects of mixed guidance modes on operator performance.

Because the graphics are relatively simple and the computational requirements are low the system can even be implemented on existing hardware (Avionics Vision Unit) used on shuttle and space station. A previous technology development project (Maida, et al) demonstrated this feasibility. The potential benefits provided by augmented reality techniques in robotic control should be considered in the modification of existing systems or the designing of future systems for operations in space.

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