Investigation of augmented reality in enabling telerobotic on-orbit inspection of spacecraft

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Exterior inspection is a crucial component of maintaining safe operations for crewed spacecraft. On long-duration missions, traditional inspection methods (e.g. crewed extravehicular activity (EVA), fixed robotic platofrms) carry high risk to astronauts, and require significant crew time and labor. On-orbit demonstrations have shown that free-flying telerobotic assets are a viable alternative, providing greater autonomy and maneuverability while reducing risk. However it is important to maintain sufficient temporal and spatial awareness of the free-flyer operator. In this research, a custom-built Augmented Reality (AR) interface was used to perform simulated on-orbit inspection of a space station for surface anomalies. The AR interface enabled command of a free-flying inspector in three operation modes: satellite (local) reference frame control, global reference frame control, and waypoint control. Performance in each of these modes, as well as analysis of the AR interactions, was assessed. Operation in the global and local frames exhibited a greater percentage of the station inspected, while the use of waypoint control showed decreased collisions between the inspecting satellite and the station. When given the option to switch command modes, subjects preferred to remain in a single mode, typically either Local or Global control. Subject feedback and NASA Task Load Index (TLX) scores suggest global and local control required less workload than that of waypoint control for the selected inspection task and waypoint method. These results demonstrate the potential for wearable AR to support on-orbit free-flyer teleoperation tasks.

Nomenclature

AR	=	Augmented reality
DOF	=	Degrees of freedom
EVA	=	Extravehicular activity
FC	=	Fixed command
FOV	=	Field of view
ISS	=	International Space Station
LDEM	=	Long duration exploration mission
SA	=	Situational awareness
SPHERES	=	Synchronized Position, Hold, Engage, Reorient Experimental Satellite
SSRMS	=	Space Station Remote Manipulator System
TLX	=	Task Load Index
UC	=	Unfixed command
VR	=	Virtual reality

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I. Introduction

FUTURE long duration exploration missions (LDEMs) will be heavily reliant on human-robotic systems for maintaining safe operations of the spacecraft and reducing overall demands on astronauts[1]. As was the case for the Space Shuttle and International Space Station (ISS), inspection tasks will be a vital component of safety operations, for maintenance, anomaly investigation, and mitigation of debris impact risk[2-4], however LDEMs necessitate a shift away from traditional robotic and crewed extravehicular maintenance towards a more flexible robotic platform. Current inspection of the ISS via the Space Station Remote Manipulator System (SSRMS)[5] is highly complex and requires excellent operator coordination, manipulation and spatial awareness skills,[6-8] even with real-time support from Earth. The long communication latencies during LDEMs will require crews to operate more autonomously, and time spent performing inspections by extravehicluar activity (EVA), or space walks, will likely be heavily restricted due to the high radiation environment[9]. Teleoperated free-flying satellites can be employed in an inspection scenario to reduce astronaut and hardware risk, and EVA time. These satellites are less massive and cheaper to orbit than their fixed robotic counterparts, and offer greater flexibility and range of motion. Numerous heritage systems including the Synchronised Position, Hold, Engage, Reorient Experimental Satellites (SPHERES),[10] NASA's Autonomous Extravehicular Robotic Camera[11] and Miniature Autonomous Extravehicular Robotic Camera,[12] and the Demonstration Autonomous Rendezvous Techbology,[13] have demonstrated the potential for free-flying operations for exterior inspection, proximity operations, and rendezvous and docking.

Free-flyer platforms pose a challenge to the operator's maintainenance of situation awareness (SA) due to the difficulty in building appropriate mental models[14,15] which are spatial representations of the environment and the free flyer, as well as the dynamics and operation of the free flyer. While the position of fixed robotic platforms such as the SSRMS can be determined from known joint angles and ranges of motion, the unconstrained motion of a free-flyer can make it difficult for observers and operators to project a free-flyer's future state and determine whether or not an action has been executed properly.[16] Additionally, veteran astronauts and EVA operators have highlighted the difficulty of localizing oneself during exterior space operations as a key limiting factor of current EVAs[§]. Inspection operations would likely be conducted in close proximity to the station and thus the design of any telerobotic interface and control interaction must support superior spatial and temporal awareness of the environment. Virtual reality (VR) and augmented reality (AR) interfaces have been suggested as a means of assisting in mental model formation[17] and reducing risk in complex telerobotic tasks.[18-21]

AR interfaces like the Microsoft HoloLens couple display and control functionalities that allow the astronaut operator to maintain awareness of their immediate real environment for safety, monitoring, and to reduce motion sickness. Robotic sytems can be controlled through direct gestural manipulation of three-dimensional virtual models of the environment[22] which can improve spatial awareness[17,23] and address previously identified interface limitations such as an inability to estimate scale,[24,25] poor spatial orientation[26] and degraded depth perception[27] during teleoperation tasks. The holographic environment can display a simulated three-dimensional exocentric view of the environment, which can be manipulated to closely resemble an egocentric viewpoint when needed. Previous teleoperation studies have shown that exocentric viewpoints can lead to improved navigaton[28] and overall task awareness,[29] whereas egocentric viewpoints support improved awareness of the immediate operational environment, although at the cost of perceptual narrowing.[30]

In adopting an AR interface for telerobotic spacecraft inspections, careful consideration must be given to the modes of control afforded to the operator. The design of display and control interfaces has been shown to be highly context dependent[31] and thus the most effective modes of control typically vary greatly from robot to robot.[32] Traditionally, on-orbit teleoperations with fixed platforms adopt lower levels of control, with robot joints and end-effectors commanded via joysticks or directional pad.[33] Joypad command (combining a joystick and directional pad) has been demonstrated for controlling similar robotic systems with the HoloLens,[22] however by decoupling the display and control, this method does not utilize the full capability of the AR interface. A popular method to control free-flying systems is the higher level spatial waypoint control,[10,34] where intermediate target states are specified by the user, with low level control inputs determined by the robot. Waypoint control has been shown to significantly improve user efficiency when completing unmanned aerial vehicle inventory tasks as compared to using a traditional low-level game controller.[35] Gestural commands like picking and placing waypoints have been shown to be effective in the HoloLens interface, being more readily adopted in the exocentric viewpoint provided by HoloLens rather than an egocentric viewpoint.[36] For a complex task like on-orbit inspection, different modes of control may be required at different stages of operation. Although there is a cognitive cost associated with switching between control modes,[37]

[§] Interviews with several veteran astronauts and current NASA EVA operators were conducted prior to this study.

reduction of overall mission time has been seen in studies where users could flexibly switch between waypoint and higher level maneuver commands for a team of robots.[38]

The goal of this study was to assess the viability of AR interfaces for controlling a free-flying satellite during a spacecraft inspection task, and making relevant operational and design recommendations for such interfaces. An AR simulation and control interface was developed to simulate an on-orbit inspection task by a free-flying robot, and assessed through an experimental study. The research considered two key questions: (1) how is the operator utilizing the AR system and various command modes during the inspection task, and (2) how effective is this utilization? It was hypothesized that Waypoint Command Mode would (1) lead to fewer collisions between the inspector and the station, (2) enable a higher percentage of the station to be inspected, and (3) have the lowest cognitive load. For trials in which command mode selection was left to the operator, it was expected that subjects would switch modes within the trial to optimize performance.

II. Augmented Reality System Design

The AR simulation was custom built for the Microsoft HoloLens Mixed Reality Platforn Development Edition 1 in the Unity 3D development environment[39] (Figure 1). The HoloLens utilizes head tracking and hand gestures to manipulate holograms within the real world. Holograms are anchored in the viewer's physical space, allowing them to walk around the holograms. Hand gestures are used to drag and reposition, rotate, and scale holograms relative to the physical space.

The simulation environment incorporates a space station model, a reference plane, an inspector satellite, and a control interface. The simulated space station configuration presented various levels of risk of collision for the inspector (Figure 2). High risk areas presented limited clearance for the inspector within the region of interest, such as highly concave geometries (e.g. nodes between connecting modules), high vertex objects (e.g. complex attachments like communication dishes) and protusions (e.g. solar panels). Low risk areas contained flat or convex geometries and limited vertices (e.g. the cylindrical surface of a module). The inspector satellite changed color when a collision with the station was detected.

During an experimental trial, a number of debris impact sites (hereafter referred to as 'anomalies') could be detected by the inspector on the exterior surface of the space station. *Critical* and *non-critcial* anomalies were differentiated by different debris impact images mapped onto the exterior of the station. To simulate 'detection' of the anomalies by the inspector satellite, anomalies remained hidden until the inspector was (1) within 1.0 m[**] of the anomaly, and (2) oriented such that the anomly was within its camera's field of view (FOV). Once detected, anomalies remained visible for the duration of the trial.

The inspector satellite was modeled on the SPHERES free-flying satellite[10], with the forward face of the inspector identified by a normal vector arrow. Movement of the inspector was restricted to a two-dimensional plane of motion, directionally in the horizontal X-Y plane and rotationally about its vertical Z axis. The inspector was commanded via a holographic control interface that registers the subject's air-tap gestures (Figure 1, Right). Anomalies would be revealed in the simulation when the relative angle between the normal to the inspector front-face and the vector from the inspector camera to the anomaly was equal to or less than half the camera's field of view (FOV). The inspector satellite was commanded in three different control modes, which could be selected using the control panel.

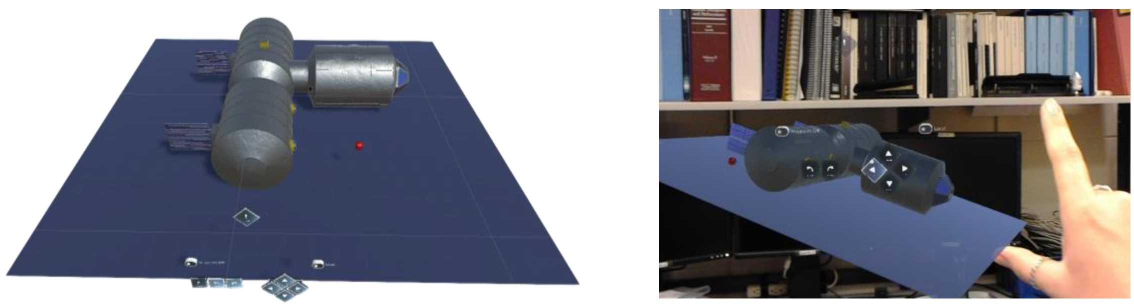

Figure 1. (Left) Complete model of the simulation environment, showing the space station, reference plane and control pad. The inspector is shown in red. (Right) The simulation implemented on HoloLens, utilizing in-built HoloLens gestural control. Here the subject is pressing the left arrow key on the control interface to move the inspector in the –Y direction in the local frame.

[**] The simulation is programmed using 'Unity units' which scale with the holograms,[40] sized so that 1 Unity unity = 2 m in the virtual world. Each station module is 4m in diameter, the inspector is 0.4m in diameter.

A. Command modes

1. Waypoint Command mode

In Waypoint Command mode the operator place a target position for the inspector within its plane of motion around the space station. These waypoints are represented by flags at the target location and can be created, set, and deleted by the subject using the holographic interface. Once created, gestural controls can be used to change the location of the waypoint, before they are set into the inspector's path. Once a waypoint is set into the path, the inspector will move towards it in a straight line at a fixed speed of 2 ms^{-1}. Additional rotation buttons on the control rotate the inspector ±15° about its vertical axis prior to or en route to a waypoint.

2. Global Command mode

The Global Command mode is a low-level control mode that provides discrete displacement and rotational commands to the inspector relative to the World Coordinate Frame attached to the space station, rather than specifying target states. Global Commands are given via a holographic directional control pad, with each discrete directional control movement moving the inspector 0.4m and each rotational command rotating the inspector 15° about its vertical axis.

3. Local Command mode

The Local Command mode utilizes the same discrete control interface as the Global Command mode; however, all directional and rotational commands are given relative to the inspector's own local body frame. If a rotation of the inspector is commanded, the local frame may no longer be aligned with the global frame.

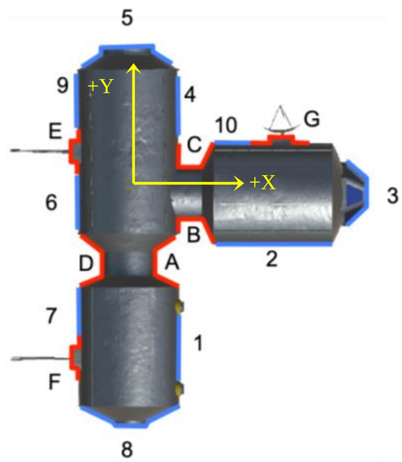

Figure 2. Risk areas of the space station. High risk areas are indicated by red lines, low risk areas indicated by blue lines.

III. Experimental Methods

A. Subjects

Twelve subjects completed the full study protocol, which was approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects (COUHES). The subject group, was aged 23 to 29 (mean age 26.08, SD = 1.93). Six subjects were placed into group A (three men, three women) and six in group B (five men, one woman). Eight subjects reported previous limited experience with either virtual or augmented reality and seven subjects reported previous relevant experience to the study consisting of video gaming, work with manipulating 3D models, and previous experimental work with telerobotics.

None of the subjects reported any physical, auditory, visual, or vestibular impairment that would impede the use of the HoloLens platform. If subjects were unable to complete all three training programs designed for the experiment then they were excused from the study; however all subjects completed training. Subjects were asked to get 6-8 hours sleep on nights preceeding their training and testing days to avoid fatigue as a confounding factor.

B. Experimental Design

The primary independent variable was the Command Mode, being either a Fixed Command (FC) Mode or an Unfixed Command (UC) Mode for the duration of a given trial. Command Mode had four levels (Waypoint – FC, Global – FC, Local – FC, and Unfixed – UC). Each subject performed the inspection task in each mode twice, for a total of eight trials. The six FC trials were always performed first. For each subject, the order of the first three FC trials (Waypoint, Global, Local) was randomized, then the order mirrored for the subsequent three FC trials to address learning effects. Each FC trial contained two critical anomalies (one high risk, one low risk) and one non-critical anomaly (low risk), with locations randomized across trial. Each FC trail had a unique set of anomaly locations.

Subjects then completed two UC trials in which the Command Mode could be freely selected and changed during the trial. The order of UC trials was not randomized. UC Scenario 1 had zero critical anomalies and 4 non-critical anomalies (two high risk, two low risk). UC Scenario 2 had one critical anomaly (high risk) and three non-critical anomlies (low risk).

The Group A subjects completed all trials using an inspector satellite with several cameras mounted around its circumference (configuration 1) providing 360° FOV. In this scenario anomaly detection was only dependent on detection distance. The Group B subjects completed all trials using an inspector with a single forward-facing camera (configuration 2) providing 45° FOV. Anomaly detection for configuration 2 was dependent on both detection distance and inspector orientation. All testing took place in a 2.5 m x 2.5 m open laboratory space under ambient light conditions. Subjects remained standing for each trial and were permitted to rest for 5 minutes between trials.

C. Experimental Protocol

1. Day 1 (Training)

One day prior to testing, all subjects were trained for approximately 120 minutes. Subjects were given an introduction to the experimental procedures, an overview of the AR interface, and required to successfully complete three training programs:

1) HoloLens Gestures – standard HoloLens tutorial to teach the in-built gestural commands.
2) Space Station Manipulation – custom-built tutorial requiring the subject to manipulate the space station model with two-handed gestures to match the position, scale and orientation of a target model.
3) Inspection Training – custom-built tutorial resembling the test environment. Subjects maneuvered the inspector along a designated path in each of the three control modes within 10 minutes. Subjects were also guided through anomaly detection and inspector collision by the researcher.

To reach a steady state level of performance and mitigate learning effects, subjects were encouraged to continue to interact with the simulation and operate the various command modes until they were comfortable with the system.

2. Day 2 (Testing)

After reviewing the training materials, subjects completed eight experimental trials of up to 390 seconds each. Each trial required the subject to maneuver the inspector satellite around the space station exterior and locate anomalies on the surface of the station. Subjects were told to complete each trial with the following performance goals, in order of priority:

1) Avoid collisions between the inspector and the space station.
2) Locate both critical and non-critical anomalies, and log critical anomalies using the *Anomaly* log button.
3) Attempt to fully inspect the exterior of the space station as quickly as possible.

The simulation ended after 390 seconds, although subjects were able to terminate the simulation early if they were satisfied they had completed their inspection. After each trial, subjects completed a Situational Awareness questionnaire and a NASA Task Load Index (TLX) survey to assess their workload.[41]

D. Performance Measures

The following raw state data was recorded every 10 frames with a sampling rate of approximately 3 Hz: *station position and orientation* (relative to world frame), *station scale factor*, *inspector position and orientation* (relative to station), and *headset position and orientation* (relative to world frame). Event-based data was also time-stamped and recorded whenever the corresponding event occurred: *control interface button presses*, *waypoint location* (when a waypoint is set), *anomaly detected* (first time an anomaly is detected by the inspector), and *collisions* (between the station and the inspector). Raw data were processed in MATLAB (Mathworks Inc., Natick, MA) to yield the following dependent variables as performance measures:

- *Collision Count*: total number of collisions between the station and the inspector.
- *Percentage of Station Inspected*: percentage of station boundary within detection distance (1 m) of the inspector's path. Note: orientation of the inspector was not taken into account by this measure.

NASA TLX composite and component workload scores were used as a measure of perceived workload during the inspection task. Subjective (self-reported) situational awareness measures were obtained from post-trial surveys. At the conclusion of all testing, subjects provided open-ended responses on their overall experience of the AR interface and their command mode preferences.

E. Statistical Analysis

Continuous dependent variables (percentage of station seen, path length, workload) were assessed using a n-way Analysis of Variance (ANOVA), with factors Subject (random), Group (fixed), and Command Mode (fixed). Subject was a nested factor within Group. If a significant effect was found in ANOVA, post-hoc pairwise comparison analysis was performed to assess the effect. Ordinal data (collision count) was assessed using a nonparametric Friedman test, with a fixed factor (Command Mode). If the Friedman test revealed a significant effect, a post-hoc Wilcoxon Signed-Rank test was performed. The order of the trials was randomized across each subject, and each order was performed once within each group. Effects of learning were not incorporated into the statistical model given the small sample size.

IV. Results

F. Effect of command mode on collision count

Figure 3 shows the average collision count between the inspector and the station across the various command modes. Waypoint Mode resulted in approximately half as many collisions as the other fixed modes, with an average collision count of 7.88 (SD = 5.75) during an average trial across both subject groups, compared to 14.46 collisions (SD = 9.39) and 15.29 collisions (SD = 9.03) for Global and Local respectively. Unfixed Mode accounted for the highest average collision count with 16.64 collisions, however the results were highly varied across subject averages (SD = 12.03).

There were no significant differences in collision performance between Groups A and B in any command mode (Waypoint: $p = 0.731$, Global: $p = 0.584$, Local: $p = 0.290$). and as such, group results were pooled for further analysis.

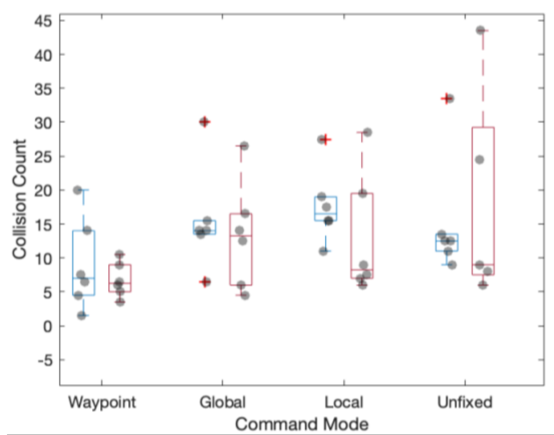

Figure 3. Subject average collision count across command modes. Blue boxplots indicate Group A, red boxplots indicate Group B and gray markers show subject average

A signficant effect of command mode was supported for collision counts ($\chi^2(df = 3) = 12.875, p < 0.001$), with post-hoc comparisons showing that Waypoint Mode had significantly fewer collisions than the other three modes ($p \leq 0.005$) and Unfixed had significantly higher collision counts ($p \leq 0.005$) than all three fixed modes, however the effect size between Unfixed with Global and Local mode count is small (r = 0.28 and r = 0.05 respectively).

G. Effect of command mode on efficiency of station inspection

The percentage of station seen in each trial measured how efficiently subjects inspected the station for anomalies. Subjects operating in Waypoint Mode inspected less than a third of the station (Figure 4). 11 of 12 subjects used the full 390 second trial time while in Waypoint Mode (Figure 5), yet only achieved an average inspection of 28.28% (SD = 10.70%). By comparison, the average percentage of station inspected across all subjects in Global Mode was 57.40% (SD: 23.41%) and in Local Mode was 55.93% (SD: 19.35%).

A significant main effect of Command Mode on percentage of station was found ($\mathrm{F}(3,94) = 28.51, \mathrm{p} < 0.001$), with the Waypoint Mode resulting in a significantly smaller percentage of station inspected ($\mathrm{p} < 0.001$ in all cases); however there was no significant difference between Global and Local Modes (p = 0.967). Use of the Unfixed Mode resulted in an average of 69.03% (SD: 20.28%), which was significantly higher than any other mode (p < 0.001 in all cases); however Unfixed trials were performed last by all subjects so these data support learning effects with the selected mode (see Section IV.I). There were effects of Subject ($\mathrm{F}(10,94) = 6.54, \mathrm{p} < 0.001$) and Subject x Command Mode interaction ($\mathrm{F}(30,94) = 2.12, \mathrm{p} = 0.010$), supporting that not all subjects had similar increases or decreases between modes. For example, Subject 5 routinely completed the test in less than 300 seconds with low percentage of station seen, suggesting that Subject 5 reprioritized

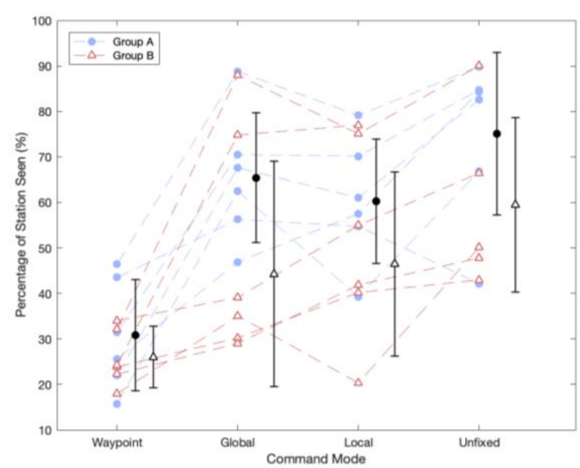

Figure 4. Subject average percentage of station seen across command modes. Blue and red markers indicate means in Group A and B respectively. Black markers and error bars show the standard deviation from overall mean.

the task goals, attempting to complete a full inspection as quickly as possible at a greater distance from the station exterior, rather than moving in closer to detect anomalies.

Group B had a lower average percentage seen compared to Group A across all command modes, but this difference was not statistically significant ($F(1{,}94) = 1.42, p = 0.260$). Group B covered signficantly less distance overall than Group A ($t\ (df = 45) = 2.88, p = 0.006$) when examining the path length of the inspector (Figure 6). A similar trend can be observed across both path length and percentage inspected, with Waypoint < Global, Local < Unfixed. This suggests backtracking along a route, while not advancing the percentage of station seen, was very small when compared to the total path length of the inspector. There was also a significant effect of subject on path length ($F(10{,}94) = 5.62, p < 0.001$), as some subjects moved the inspector significantly less distance on average than others. An interaction effect of Subject x Command Mode was also observed ($F(30{,}94) = 3.1, p < 0.001$). While many subjects trended in a similar direction, Figure 6 shows several subjects in both groups performed much better than the group mean in the Global condition, with an observationally lower standard deviation in Local mode.

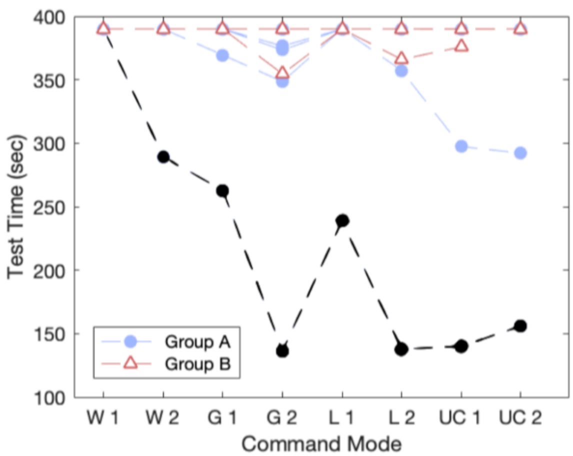

Figure 5. Subject total test time across all trials. Blue markers and red markers indicate subject times in each trial within Group A and Group B respectively. Subject 5 is highlighted in black.

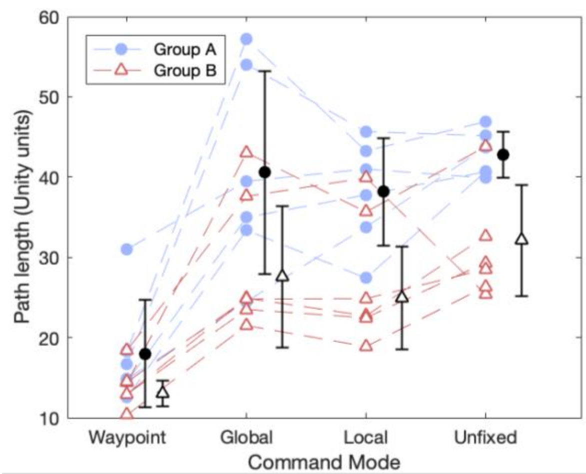

Figure 6. Average path length across each trial. Blue markers and red markers indicate subject values in each trial within Group A and B respectively. Black markers and error bars indicate the standard deviation from the overall mean.

H. Effect of command mode on workload

Trials conducted in Waypoint Mode produced the highest average composite workload score of 73.14 (SD = 14.67) while the Global, Local, and Unfixed Modes had average workload scores of 61.36 (SD = 19.52), 61.74 (SD = 15.08) and 52.32 (SD = 21.56) respectively (Figure 7). The effect of command mode was significant ($F(3{,}94) = 7.86, p < 0.001$), with post-hoc comparison showing Waypoint had a significantly higher composite workload score than either Global Mode ($p < 0.001$), Local Mode ($p = 0.009$), or Unfixed ($p < 0.001$). Global and Local Mode were not significantly different ($p = 0.991$), however the Unfixed Mode had the lowest composite workload score, significantly lower than Waypoint, Global ($p = 0.007$) or Local ($p = 0.005$). Observationally, subjects in Group B tended to award lower workload scores than Group A; however no significant effect of Group was observed ($F(1{,}94) = 0.97, p = 0.348$).

There were significant differences between the subjects' ratings of composite workload in the trials. For example, subject ratings range from approximately 10 to 95 out of a possible 100 for Unfixed Mode. Some subjects were observed to consistently award a high workload rating across all four modes, while others had different orderings of the ratings across modes. The ANOVA supported a main effect of Subject on composite workload score ($F(10,94) = 7.97, p < 0.001$), and interaction effect of Subject x Command Mode ($F(30,94) = 2.45, p = 0.003$).

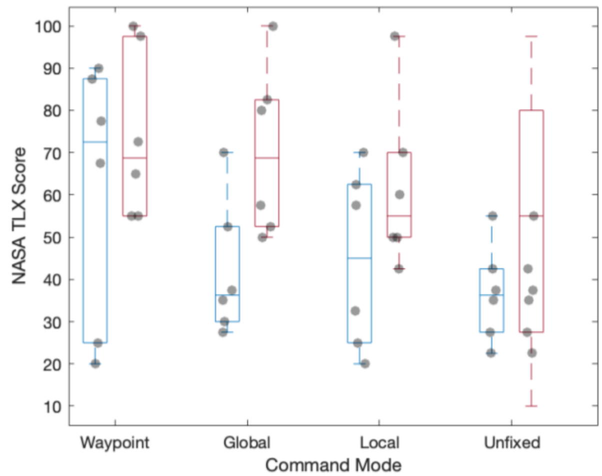

Figure 7. NASA TLX average composite workload across command modes. Blue and red boxplots indicate Group A and B respectively, gray markers show the subject average score.

I. Unfixed command mode effects

Our hypothesis that subjects would switch among modes when operating in the Unfixed mode was not supported by the observed behavior. Five out of six subjects in Group A performed the inspection exclusively in a single mode of control. Four of these subjects remained in either the Global Command Mode, or a globally-oriented Local Command Mode (performing no rotation of the Local Frame). One subject employed a single rotation of the local frame, and performed the entire trial in Local Mode; however no other rotations were recorded. Only one subject opted to switch from the Global Frame to the Waypoint Mode to place a single waypoint in UC 1.

Conversely, four out of six subjects in Group B utilized the Local Mode exclusively for both Unfixed trials. One subject exclusively used the Global Mode for both UC trials. Subject 12 is the only subject in both groups to interchange between Global and Local Modes of command during the trials. In UC 1, subject 12 changed command mode 10 times, and in UC 2 the subject changed command modes 6 times. Evaluation of the command modes selected and path taken by the inspector reveals that the Local Command mode was utilized when the subject desired to move in a direction not orthogonal to the axes of the space station.

J. Operator AR behaviours

The two primary interactions with the AR interface, rotating the station and scaling the station, allowed the subject to change their viewpoint of the station and inspector. The rotations used by each subject were broadly categorized into three preferred viewpoints: operating in a perspective viewpoint, operating in a plane view (where the entire plane of motion can be seen), and operating in a front-on view (on or near the plane of motion). Operation in the front-on view was typically characterized by limited rolling of the station, merely rotating the station about the vertical axes as the inspector traversed around the station. Two subjects remained in one preferred viewpoint for the duration of each of their trials, although this preferred viewpoint changed between trials. The remaining 10 subjects moved through different viewpoints within each trial. Four subjects performed over 50% of every trial in the perspective viewpoint, with the remaining subjects switching into this viewpoint at least once per trial. Seven subjects adopted a strategy of completing the first half of the trial in one viewpoint, with slight modifications to the angle, then switching to a different viewpoint for the remainder of the trial, typically when the inspector moved to the side of the station furthest from the starting position (risk areas 4,5,10,C,G). Conversely, one subject exhibited switching between viewpoints for the duration of every trial, changing rotation angles every ~10-20 seconds. Another subject maintained a front-on view for each fixed trial, and routinely made checks of the wider environment by quickly switching into and out of an aerial perspective for several seconds.

Scaling could occur either through gestural commands or by adjusting one's physical position relative to the holograms by moving in the room. Scaling allowed subjects to get closer to the station and resolve greater detail, either to detect anomalies or better determine proximity. Gestural scaling would change the physical space occupied by the hologram, whereas physical motion would change the visual perception of scale. Two subjects appeared to use gestural scaling to coarsely adjust the size of the station, then finely tune the size by changing their physical distance to the hologram, and a further two subjects would continually gesturally change scale, but then adjust their physical distance to maintain a consistent visual scale throughout the trial. In several trials the remaining subjects were observed to continually gesturally scale the station up or down over the duration of the trial, most commonly at the high risk areas of the station. Six subjects performed a substantial gestural scale up of $\sim 50 - 75\%$ when reaching high risk areas such as region A, D, E, and F or the higher convexity areas at regions 3 and 5 (Figure 3). This is likely due to a desire to avoid collisions, or to inspect the region for anomalies since the model was typically scaled down after inspection of this area was complete.

V. Discussion

The research considered two key questions; how is the operator utilizing the AR system and various command modes during the inspection task, and how effective is this utilization? It was hypothesized that (1) Waypoint Command Mode would support fewer collisions between the inspector and the station, (2) enable a higher percentage of the station to be inspected, and (3) have the lowest cognitive load. The significant decrease in collision count when operating in the Waypoint Mode, as compared to the other fixed modes, supports Hypothesis 1. As was highlighted by Szafir et al.,[42] it was hypothesized that the Waypoint Mode encouraged subjects to plan and place waypoints in a globally-oriented frame which would improve spatial understanding, a criteria identified as critical to effective teleoperations.[14] Subjects operating in Global and Local mode more closely adhered to the station boundary during their inspection, particularly in high risk regions, while subjects appeared to adopt a more cautious strategy when operating in Waypoint Mode. This behavior may be driven by the implementation of Waypoint Mode as operating closer to the station boundary would have required an increased number of waypoints due to the linear behavior between waypoints.

The gestural control method used by the HoloLens would seem to support a higher-level control mode for maneuvering a robot, rather than low-level incremental motions of manual control. In practice, Waypoint Mode yielded the lowest average percent of station inspected with the shortest path length, while low level methods of fixed control (Global and Local) supported increased inspection efficiency, and thus Hypothesis 2 was not supported. There was no significant performance difference between the Global and Local modes, likely a consequence of subjects primarily orienting the Local Mode frame to align with the World Frame of the station and thus using the Global and Local modes in a similar manner.

Waypoint mode generated the highest composite workload score, and so Hypothesis 3 was not supported. Subjects expressed frustration at time required for waypoint mode in their qualitative feedback, as the method of generating, moving and setting a waypoint proved cumbersome. Subjective assessment of workload was supported by the lower path length performance yet full use of the trial time. While previous studies have shown that waypoint mode is an optimal choice for controlling free-flyers, the interface in this study differed significantly, requiring subjects to physically pick up and place waypoints in the holographic environment rather than select locations with a pointer on a screen and only allowed subjects to place one waypoint at a time. Careful consideration must be given to future designs of waypoint control in the context of the task being performed. The use of a single waypoint at a time was not well-suited to the patrol inspection task users were asked to perform in this experiment. The improved collision avoidance and cautious operator behavior demonstrated in Waypoint mode suggest the current waypoint mode would be more appropriate for a single point inspection, where operators target a specific location on the station exterior for a more detailed inspection, rather than examining the entire exterior of a station for possible anomalies. Waypoint control could be modified to be more aligned with a perimeter patrol task by enabling *a priori* planning with multiple waypoints, or having the paths between waypoints use proximity information to edge follow an object.

Its important to note that this study limited the inspector satellite to a two-dimensional plane of motion. While the majority of subjects expressed or demonstrated a preference for either the Global or Local Mode when operating the inspector, the restricted plane of motion meant that a simplistic directional pad was sufficient to provide control. Controlling a robot in 6 DOF, as would likely be the case on-orbit, would necessitate a redesign of the lower-level control interface to enable an additional 3DOF. Insights provided on the design of waypoint interfaces would be readily applicable to a three-dimensional plan of motion, as waypoints are typically placed by a single point control (in this case moving and placing the waypoint). Future studies with 6 DOF tasks are needed.

When given flexibility over the control modes, subjects tended to perform UC trials in a single mode of control, with the exception of subject 12, who routinely changed modes in both UC trials. Subjects in Group B tended to exclusively use Local Mode and Group A subjects operated in either the Global mode or a globally-oriented Local mode. Group B's preference for the Local Command Mode could be a consequence of the single camera viewpoint required for inspection. Using a Global Mode while requiring re-orientation with respect to a Local Frame could lead to poor spatial understanding due to the shift in reference frames, as was found by Stoll et. al.[43] Subject 12, the only subject to routinely swap between Global and Local modes, generated a sequence that utilized the Local Mode to perform maneuvers around irregularly shaped portions of the station (e.g. the cupola and the ends of modules) before returning to the Global Mode to traverse long flat sections of the station. Subject 12 increased their percentage of station seen in the Unfixed mode trials compared to the FC trials. In their post-experiment evaluation, Subject 12 highlighted their preference for the Unfixed Mode. Subject 12 also preferred to remain in a single view (perspective view) within each trial, one of only two subjects to exhibit this behavior.

As was observed by Wang and Lewis,[44] the subjects in this study generally preferred an exclusive command mode over toggling between them, instead choosing to optimize performance through changing scale and viewpoint. For future AR design interfaces, these results suggest that enabling flexibility of control may be traded-off with flexibility in the choice of display. Further studies should examine if the mental workload cost of control switching or the time taken to switch outweighs any performance benefits, as previous studies have shown that associated costs with switching modes contribute to the choice of an exclusive command mode.[37,38] Notably, several subjects expressed a preference for the unfixed option over the fixed option in their qualitative feedback, suggesting subjects preferred the autonomy to choose their desired command mode, even if they did not change it within the trial.

AR was selected as the display and control interface for this study as it affords the viewer a flexible approach to selecting a(?) viewpoint. Subjects exhibited individual preferences for their preferred viewpoints and station scale, and how often these were modified. Our results align with previous studies that highlight egocentric viewpoints support improved perception of the immediate environment,[29] as subjects typically zoomed into the model (essentially giving them an inspector view) when navigating high risk and high convex areas that posed a significant risk of collision (e.g. the front-on view), before returning to an exocentric viewpoint to continue navigation (e.g. the perspective view). Analysis of the AR interactions also provides insight into subject priorities during a trial. Plane views afforded subjects a view of the station extremities, whereas front-on viewpoints hindered proximity perception, but supported anomaly localization. Perspective viewpoints, used by the majority of subjects, supported a balance of both boundary awareness and anomaly localization. Subjects that routinely switched viewpoints seem to be attempting to utilize the benefits of each and thus maintain performance across all three performance criteria. Rather than switching control modes to optimize performance, subjects preferred to switch viewpoints to support the different performance goals, such as collision avoidance or more efficient path planning and therefore a faster inspection time, however the current study was not designed to examine how performance was affected by the choice of switching display versus switching control mode.

The AR gestural design was qualitatively assessed by subjects and received mixed feedback. Some subjects enjoyed the flexibility the interface gave them in customizing their viewpoint through the trial, while others found the imprecision in rotating and scaling the station to be frustrating. As was suggested in qualitative subject feedback, future design iterations could incorporate preset viewpoints that automatically move the station with high precision when selected. Care should be taken in switching viewpoints as shifts in perspective can cause operators to become disoriented as they reorient their mental model.

K. Limitations and Future Work

There were several restrictions of the hardware and software used for this study that should be addressed in any future studies. The HoloLens generation 1 has a highly restrictive field of view making it difficult for certain gestures to be detected and restricting subjects' view of the holograms, which may have hindered performance. In the Unity 3D Gaming Engine used to build and render the simulation, simple 3D shapes such as cubes or ellipsoids were used to model the collision boundaries of the space station surfaces. As a result, there are several areas where the rendered surfaces are misaligned with the collision boundaries which could result in missed collisions.

Traditional space teleoperation displays and interfaces use fixed 2D camera views and physical control interfaces (joysticks, keyboards etc) which can impose higher cognitive loads, and potentially degrade performance.[7,46] In constrast, the AR interface synthesizes the visual information into a unified 3D representation and could improve situational awareness and decrease cognitive workload but with a trade-off of additional physical workload due to the gestural control. Several subjects reported fatigue after completing the 8 trials and commented that a game controller might be easier to use than the gestural controls. Future studies should compare current telerobotic controls and displays with a gesturally-controlled AR HMD interface to assess this tradeoff between physical and cognitive workload. Physical fatigue may be less of a concern in microgravity as gestures will not require acting against gravity. Finally, it should be noted that all subjects had limited experience with AR interfaces and anomaly detection tasks. With longer exposure to the technology, strategies may continue to develop and new strategies emerge.

VI. Conclusion

This study examined the use of a custom AR interface for performing telerobotic inspection tasks on a simulated space station. Gestural controls were used to command a small satellite in three command modes (Waypoint Mode, Global Mode,and Local Mode). Both low-level manual control modes were found to support increased efficiency in inspecting the station exterior whereas Waypoint Mode was found to support better collision avoidance. Results across multiple performance criteria suggest the design of the Waypoint mode was more appropriate for single point inspection, rather than the patrol task explored in this study. When given the option to dynamically select modes, subjects preferred to operate in a single mode of control and usually one of the low-level manual control modes. Independent of control mode, throughout all trials subjects dynamically modified their viewpoint of the station to optimize performance. AR interfaces present an option for space telerobotic interfaces; however, careful consideration should be given to their design to ensure optimized performance. In this study, display flexibility was implemented during early usage of this AR interface, and results of this study show that display flexibility may be traded off with control flexibility.

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