Automated Augmented Reality Operator Aids for Space Robotic Teleoperations

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Abstract

Collision-free teleoperation of robotic arms is a critical requirement on the International Space Station (ISS). Astronauts manually navigate robotic arms using video views and are hindered by factors such as limited fields of view, display-control misalignments and poor depth perception. Augmented reality (AR) interfaces can be useful in mitigating many of these issues. An AR technique that synthesizes computer-generated end-effector trajectories in multiple exocentric camera views of the remote robot in the form of colour-coded 3D visual aids is presented. Using these visual-aids, the user manipulates the end-effector through a series of rotations and translations from start to goal. An experiment to determine manual end-effector performance under three conditions was conducted: with AR (AR), with the same aids presented in a stand-alone 3D VR display (VR), and finally, a combination of the two (AR-VR). The AR and AR-VR constrained the robotic arm to well-defined safe regions while VR alone led to significant deviations. The results of the experiment are presented along with a discussion on the benefits and limitations of automation-supported operator aiding during robotic tele-operations.

Introduction

In low earth orbit missions, manual tele-operation of robotic assets on the International Space Station (ISS) has remained the modus operandi for the past 30 years, despite dramatic advances in robotics and automation in Earth applications and in planetary exploration missions. There are a number of contributing factors that have led decision makers to sustain manual operations on the ISS. Many of the key challenges arise due to a gamut of human factors issues including the integration of automation into existing operational procedures. It is well known that increased automation can substantially augment human-robot interaction and recent reports bolster this need (Billman, et al., 2011). Before exploring these details, it is worthwhile to first revisit the challenges faced by robotic operators on the ISS and to review methods to mitigate these challenges.

ISS robotic arms such as the Canadarm2 are guided by manual hand-controller inputs and camera feedback. Within this closed loop system, two factors impact operator performance. The first is the spatial relationship between the robotic arm and the cameras. The second is the control technique employed to manipulate the

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multi-degree of freedom (and large) arm (Chintamani, 2010). A technique called resolved control is used to manipulate the arm using the end-effector's coordinate system (Cartesian) as the reference. This inverse kinematics solver provides six degree-of-freedom control (three axis rotation and translation) of the end-effector while ensuring that geometric constraints due to the arm mechanics are accounted for.

When the end-effector is rotated or translated, the arm configuration (angles) changes in order to achieve the required end-effector pose. This can lead to contact with objects in the workspace if the operator is not careful, Figure 1. Exacerbating this issue are camera limitations such as, depth perception and field of view. Constantly changing lighting conditions in orbit further complicate the problem. Human performance is understandably impaired by these factors.

The authors' previous work on this topic has aimed at mitigating these difficulties. An analysis of manual control performance and identifying limitations in camera-based teleoperation was presented in Chintamani et al. (2006). The main finding was that even simple navigation tasks challenged proficient users. End-effector navigation in an empty workspace was characterized by non-smooth trajectories resulting from the separation of control inputs onto unique rotation and translation hand-controllers. Among other contributing factors for these characteristic trajectories are display-control misalignments, which arise due to the mismatch between the viewed end-effector reference frame (on the display) and the hand controller reference frame (Chintamani et al., 2011). The hypothesis was that augmented reality (AR) techniques could reduce a number of difficulties in teleoperation and could also see use in more advanced human-robot interaction.

The first AR display developed by the authors was a simple graphic reference frame rendered in 3D and overlaid on the end-effector in the camera view (i.e. using AR). The same AR frame could be viewed simultaneously in perspective from multiple camera views. Each axis on this AR frame was colour-coded and mapped to the hand-controller axes using similar colour coding. User studies demonstrated significant reductions in navigation errors and travel distance (Chintamani et al., 2010). Analysis of the results demonstrated that this AR technique resulted in smoother trajectories. To further corroborate these results, a follow-up study to measure operator cognitive load when exposed to conditions of display-control misalignments was conducted (Chintamani et al., 2011). Response accuracy and reaction times were measured with and without the AR frames. The AR frames dramatically reduced response time to misaligned orientations of the end-effector. These results led to the conclusion that operator-aiding AR teleoperation displays were beneficial for free-space navigation but left a question open: can similar displays support advanced human-robot interaction, for example: path planning and obstacle navigation?

End-effector navigation in close proximity to other space infrastructure and through narrow passages is generally avoided during missions. Limited depth perception from the camera views makes proximity to obstacles difficult to estimate while the robot's kinematics (singularities and mechanical limits) makes it at times impossible to reach a desired position or orientation. These factors can increase operator workload and compromise safety. One mitigation technique is to increase robot autonomy. Space agencies agree that an increase in robotic autonomy is needed to enhance current and future space missions. Supervisory control has for long been a desired aim in telerobotics (Sheridan, 1986) however, operator “out-of-the-loop”, vigilance issues and reduced situational awareness have excluded its use (Billman et al., 2011; Kaber et al., 2000). This implies that task allocation between autonomous robots and humans along with modalities for interaction must be understood. The issues of reliability and trust must be reviewed as well. To bridge this gap in the safety-critical domain of human spaceflight, methods are needed to facilitate human-automation interaction and autonomy can be incorporated so that it serves only as an information-generating agent: instead of guiding the robot, automation is used for the sole purpose of operator guidance.

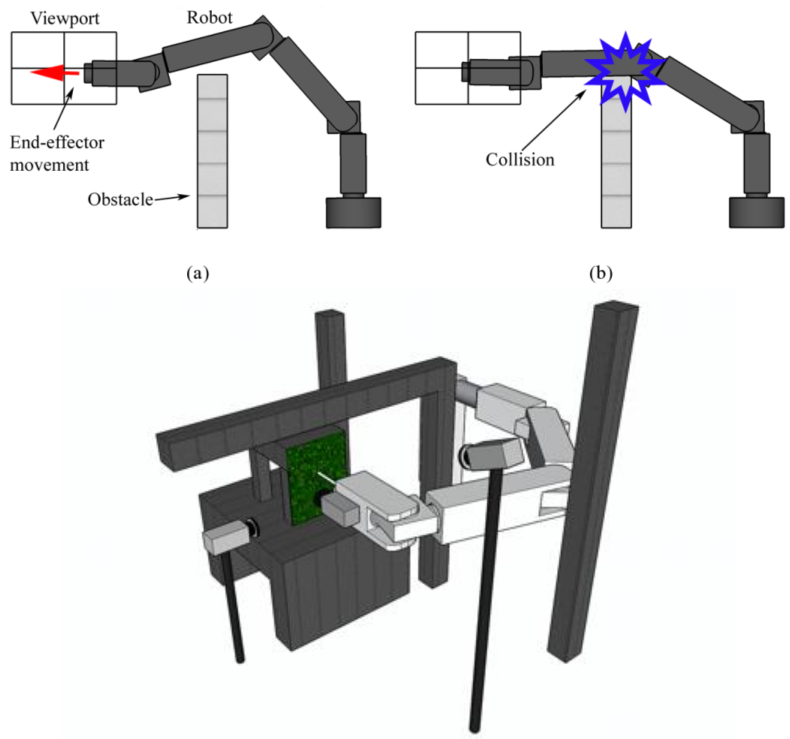

Figure 1 Robotic arm tele-operation is affected by limited field of views and cluttered environments. Human performance challenges increase in cluttered environments.

We present a telerobotic system based on this principle. Upon user request, a planning agent generates a collision-free end-effector trajectory or plan. The plan is an alternating sequence of translation and rotation operations required to move the end-effector from start location to a goal location. Each translation-rotation pair forms a waypoint in the plan. Our system uses AR to present this plan in a simple manner using concepts validated in earlier studies, primarily the colour-coded AR reference frames (Chintamani et al., 2010).

In this article, we present a first step towards the interaction between autonomous planners and human operators in robotic arm teleoperation using AR displays. In a previous work, a similar AR display was presented where the plan was described as a simple sequence of collision-free points (Chintamani et al., 2009). Many of the shortcomings of that system are addressed here. The aim is to identify if automation support can increase teleoperation safety. In addition, virtual reality (VR) as an alternative to AR is studied.

Methods

Participants

Eighteen participants volunteered for the study with age ranging between 20 to 50 years and were not compensated for their time. This study was approved by the Wayne State University Human Investigation Committee under HIC protocol 082105B3E (R).

Experiment Task

The aim of the task was to navigate the end-effector of an RT100 robot arm from two fixed start locations to a goal location in a cluttered environment. An obstacle course was assembled in the robots worksite ensuring that end-effector navigation task was challenging. Two cameras were placed in this environment, Figure 2. A location between the obstacles was selected as the goal location. Participants were asked to navigate the end-effector to this location using the AR and VR displays described below.

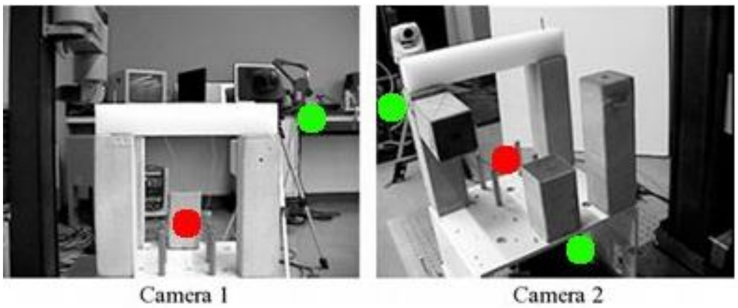

Figure 2 Camera views and obstacle environment selected for the experiment (green: start locations, red: goal location)

The camera views were separately displayed on LCD monitors (1280 x 800 pixels) and a third monitor was used to view path information using a VR display. AR views were generated over the live camera views on the two monitors. Participants used two colour-coded joysticks to control the rotation and translation of the end-effector.

Generation of Navigation Plans: Two collision-free navigation plans from the two start locations to the goal location were generated by a software planning agent (using probabilistic search techniques). Implementation details on the planning agent are available in Chintamani (2010). The AR navigation display loaded these plans and rendered the corresponding 3D graphics. A similar approach was taken for the VR display.

AR Navigation Display: The system begins with the end-effector positioned at the start location. The first target orientation is rendered as 3D colour-coded torii (Figure 3a). Collision-free line segments (translation cues) are presented as a cylinder that changes colour as the end-effector translates over it. The user's task is to rotate the end-effector attached AR reference frame into alignment with the torii. For example, in Figure 3b, the user first brings the green axis into alignment and then the red axis (Figure 3c).

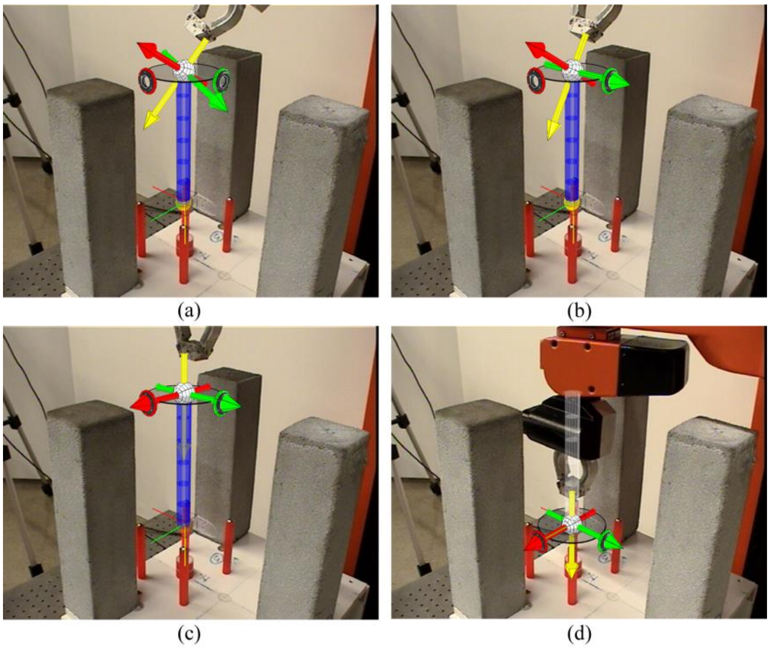

Figure 1 Manual method of use using the AR navigation display

This operation automatically points the yellow axis towards the goal location (in the direction of the blue line). The user then translates the end-effector along the yellow axis. In this simple example, a single waypoint is presented for clarity and plans can include one or more waypoints. When the end-effector traverses 75% of the segment length, the next pair of orientation and translation cues is automatically displayed.

Each waypoint can contain one or more orientations that can be reached at a particular location. The planning agent includes this information (if available) in the plan. The system is "smart" in the sense that it detects user difficulties in reaching an orientation and updates the orientation cue (if another orientation is available). More details on this system are described in K. Chintamani (2010).

VR Navigation Display: This display presented the same information as the AR navigation display, that is, 3D models of the robot, obstacles and the plan in a virtual environment. This user interface was displayed on the third monitor with interactive features such as pan, tilt, rotation and zoom to obtain different perspectives of scene.

Experiment design

A between-groups design was used (*group* x *plan* x *trial*). Participants were randomly distributed into three groups; AR, VR and AR-VR. The AR group navigated the robot using the AR navigation display. The VR group was trained to teleoperate using camera views (no AR) and the VR display. The third group, AR-VR presented path information in both AR and VR. *Plan* consisted of two pre-generated navigation plans titled *plan 1* and *plan 2*. Three trials were administered for repeated measures. A time limit of 7 minutes was imposed on each trial. End-effector deviation from the prescribed trajectory (mm) and end-effector distance were the dependent variables. Participants were trained until confident with the system controls. Obstacle geometries and the plans used for training were different from those used in the experiment to prevent learning effects.

Data Treatment

The data for these variables were found to be non-homogeneous with regard to variance. Levene's test for equality of error variances: end-effector deviation, $F_{(5,102)}=14.43$, $p < 0.05$ and distance, $F_{(5,102)}=7.56$, $p < 0.05$, were obtained. Given the non-homogeneous data, the data cells corresponding to the experimental conditions, *groups* x *plan* (3x2) were labelled from 1 through 6 under the fixed factor, *condition*. The Kruskal-Wallis test was run with *condition* as the independent variable and rank of end-effector deviation and distance as the dependent variables. Effects were tested post-hoc using Tukey's HSD test.

Results

The effect of condition on deviation was significant, $F_{(5,107)} = 30.76$, $p < 0.05$. Mean deviation for the VR group was significantly higher ($p<0.05$) that the AR and AR-VR groups. Comparisons of each factor showed that the plans had no influence on deviation for AR and AR-VR, Figure 4.

Condition also had an effect on distance, $F_{(5,107)}=34.09$, $p < 0.05$. It should be noted that the two plans were of different lengths. Correspondingly, a significant difference between plans was observed ($p<0.05$), Figure 5.

For plan 1, mean distance for the VR group was significantly higher than both AR and AR-VR ($p<0.05$). No differences were seen between AR and AR-VR in terms of distance. For plan 2, no statistically significant mean differences in distance were observed between the three groups.

No collisions with the obstacles were recorded with the AR and AR-VR groups. Several trials in the VR group however, resulted in collisions with the obstacles.

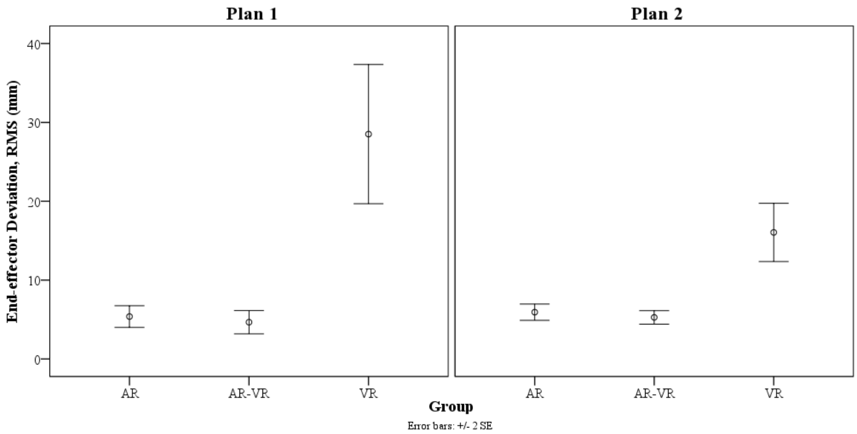

Figure 4 End-effector deviations for the AR and AR-VR groups were very low in comparison to the VR group.

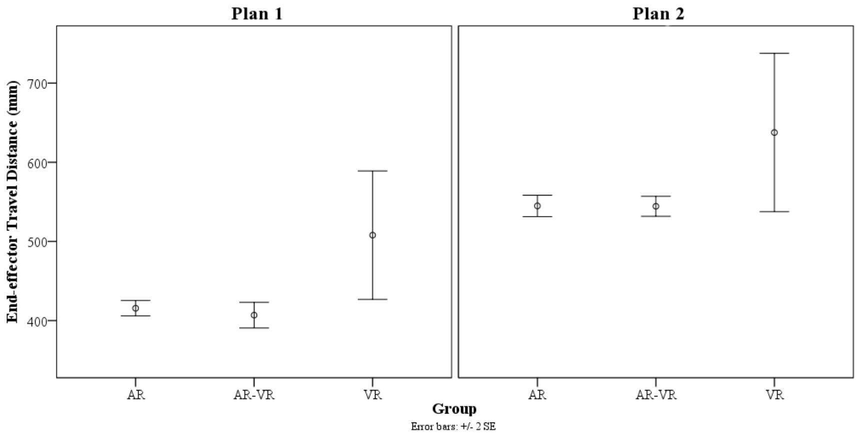

Figure 5 Overall travel distances were closer to the distance prescribed by the planning agent in AR and AR-VR in comparison to VR alone.

Discussion

The results demonstrate that the AR navigation display performed better than the VR display, with mean end-effector deviations ranging between 4.7 mm and 5.9 mm for the AR and AR-VR groups. In fact, the improved graphic aids reduced deviations to values lower than those obtained in the previous version of this system where deviations ranged between 9 and 12 mm (Chintamani et al., 2009). Deviation was not influenced by plan demonstrating that these low values could be achieved irrespective of the plan generated or viewing conditions.

Although the end-effector trajectories in the VR group were similar to those recommended by the plans, the deviations were much higher. Deviations as high as 84 mm for plan 1 and 34 mm for plan 2 were observed for the VR group. These trajectories are presented in Figure 6. These results have implications for space operations. Navigating within a recommended “safe” zone can be beneficial and any aids that restrict the end-effector to this zone are advantageous. Furthermore, the AR and AR-VR groups produced trajectories that were hardly distinguishable across trials.

The AR display also enabled lower travel distance compared to the VR group; that is, the navigation plan’s length and the distance travelled were nearly the same. The VR group completed the task with more distance travelled by the end-effector. In the experiment, the plans computed by the agent neared the minimum distance between start and goal (considering robot-obstacle clearance). However, the planning agent was not designed to minimize the change in orientation when moving between plan segments. Overall performance would have been better if this process was optimized. Despite these limitations, minimizing the effort needed to navigate a robot is a significant advantage in energy-, time- and safety-critical space operations.

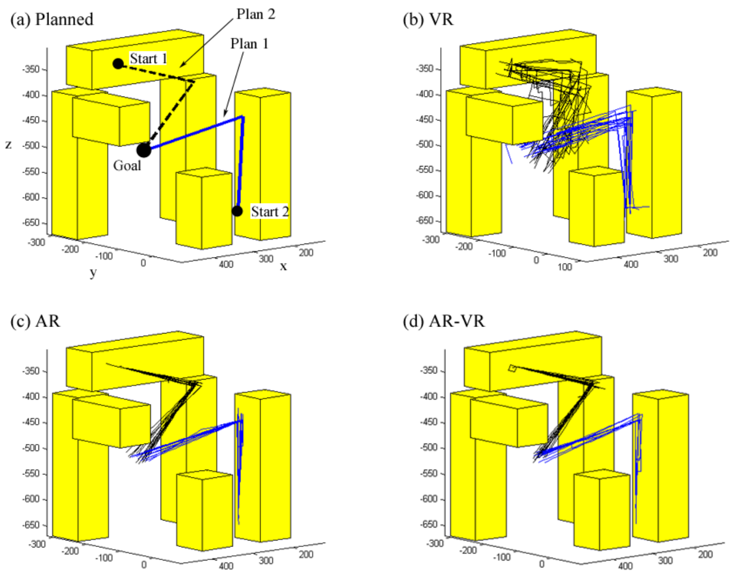

Figure 6 Agent generated plans and trajectories generated by the VR, AR and AR-VR groups

Conclusion

In this study, a planning agent autonomously generated motion plans for a robotic arm and delivered this plan via an AR display to the user for manual execution. Our main hypotheses, that is, an improvement in navigation performance was quantitatively validated. There are however, a number of improvements and questions that can be raised on the principles of the system.

First, if the robot’s environment is known and the planning agent can create a plan autonomously then why not just automate the robot? This was Roseborough’s dilemma (Roseborough, 1988) and a perplexity that frequently occurs in many complex systems including autonomous transportation systems, air traffic control and robotics.

Second, there is the issue of operator trust in the plans presented in the AR navigation display. Does the user assume that the plan is valid and error-free? Participants in the AR-VR group for example, seemed to trust the AR display blindly rarely verified the robot's status in the VR model[1]. In the same study and not presented here, operator situational awareness using a 3D environment and trajectory reconstruction test was evaluated where it was found that most users could not reproduce the trajectories in a scaled 3D model of the robot's environment[2] post-trial, Figure 7.

Figure 7 Environment and trajectory reconstruction test used to evaluate user situational awareness

Both Roseborough's dilemma and trust in automation are crucial for such AR navigation displays. Indeed, if sufficient automation is available to achieve a task, human involvement is unnecessary. In addition, the need for increased automation in space robotics and the need for a change from manual operations to supervisory control have been recognized in recent agency publications. Billman et al mention the need for efficient task allocation between human and automation in (Billman et al., 2011) while Ambrose et al state the need (TA4.4) for autonomous manipulation systems along with interfaces that "enable a human to rapidly understand the state of the system under control and effectively direct its actions towards a new desired state" (Ambrose et al., 2012).

In this regard, the AR navigation display although restricted in here to the manual navigation of robotic arms, could be of dual use: 1) to augment manual control, that is, providing the best trajectories to take, safety or "no-fly" zones and optimal orientations that minimize energy consumption or speed up the overall task; 2) It could be used as a display that, as specified by Ambrose et al, enhances the operator's situational awareness of an automated robot's internal state, goals and expected state(s). In fact, this is exactly what is needed to enhance operator trust in the autonomous system's goals and expected states. One way of increasing trust in

[1] Evidence based on an observation of participant behavior during experiments.
[2] These results are described in greater detail in Chintamani (2010).

the autonomy could involve the use of AR-based simulations that allow the user to browse through the various states of the automation, for e.g. navigating a virtual AR robot in the same camera view that shows the remote robot (see examples in Chintamani, 2010, Chapter 5).

Today, no standards or guidelines exist to adequately define such displays and as an emerging technology, AR is a viable candidate. The ability to display automation processes within the same display space in a shared frame of reference (a unified display) as the robotic system being controlled is perfect for a range of space mission robotic scenarios such as human-robot cooperative tasks (close proximity) and remote robot monitoring.

Acknowledgements

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