Experimental Evaluation of Teleoperation Interfaces for Cutting of Satellite Insulation

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***Abstract*— On-orbit servicing of satellites is complicated by the fact that almost all existing satellites were not designed to be serviced. This creates a number of challenges, one of which is to cut and partially remove the protective thermal blanketing that encases a satellite prior to performing the servicing operation. A human operator on Earth can perform this task telerobotically, but must overcome difficulties presented by the multi-second round-trip telemetry delay between the satellite and the operator and the limited, or even obstructed, views from the available cameras.**

This paper reports the results of ground-based experiments with trained NASA robot teleoperators to compare our recently-reported augmented virtuality visualization to the conventional camera-based visualization. We also compare the master console of a da Vinci surgical robot to the conventional teleoperation interface. The results show that, for the cutting task, the augmented virtuality visualization can improve operator performance compared to the conventional visualization, but that operators are more proficient with the conventional control interface than with the da Vinci master console.

I. Introduction

Most present-day satellites are designed with a finite service life limited by on-board consumables—principally fuel for orbital maneuvering and attitude control. NASA Goddard Space Flight Center's (GSFC) Satellite Servicing Projects Division (SSPD) is currently developing the capabilities necessary to refuel spacecraft in low Earth orbit.

SSPD's concept for satellite servicing is to launch a servicer spacecraft with robotic arms that can be teleoperated from the ground, with round-trip telemetry delays between 2 and 7 seconds, or can operate with limited autonomy based on sensor feedback. The autonomous mode would be used for tasks requiring low-latency response to sensor inputs, such as the capture of the client satellite. Once the servicer is docked with the satellite, proximity operations would be performed telerobotically. There are, however, several challenges to telerobotic control of a robot on orbit by an operator on the ground. These include the communications time delay and the limited visualization of the remote environment, which is restricted to the views from cameras mounted near the robot tool or on the deck of the servicing spacecraft.

We recently reported the development of an *augmented virtuality* interface [8], [9], where the operator interacted with a *virtual* 3D model of the satellite that was augmented by projecting the *real* images from the robot tool camera onto the satellite model. The 3D model was obtained by performing 2D/3D registration between a 3D model of the satellite and multiple 2D images (from a robotic survey) [8] and by reconstructing "unknown" objects (i.e., objects not in the satellite CAD model) from the 2D images [9]. A multi-user study was performed to evaluate the system, subject to a telemetry time delay of 5 seconds between master and slave, for a task that emulated a satellite servicing operation [9]. Limitations of the prior study were that the human subjects were not trained NASA robot operators and the task, drawing on the satellite surface, was not an actual servicing task. This paper reports the results of an experimental study to compare the proposed augmented virtuality visualization to the conventional camera-based visualization for an actual servicing task with trained NASA robot teleoperators. In addition, we report a keyboard and graphical user interface (GUI) that more closely emulates the conventional robot control interface used by NASA, and report an experimental evaluation of task performance with this interface in comparison to our previously reported teleoperation console, [8]–[13], based on the master console of a da Vinci surgical robot [2].

II. Background

In May 2016, NASA announced the Restore-L mission [5] to demonstrate telerobotic refueling of Landsat 7, a U.S. government-owned satellite in low Earth orbit.

The majority of spacecraft, including Landsat 7, are covered in a thin blanket of thermal insulation material called multi-layer insulation (MLI) [1], which must be removed prior to servicing. MLI is composed of thin layers of insulating foil stacked together in a blanket which is then wrapped around the spacecraft to help regulate the temperature of internal components.

Different cutting tools may be required for differing MLI geometries and to accommodate a variety of underlying equipment and surfaces. NASA's Robotic Refueling Mission (RRM) [6] and prior research at JHU [10]–[13] used a blade to cut through tape that secured an MLI patch over the refueling valve. A similar blade was used to demonstrate telerobotic cutting of MLI tape in a cross-country experiment between the University of Pennsylvania and the Jet Propulsion Laboratory in California [7]. In many cases, items of interest that protrude from the flat paneling of a spacecraft, such as the refueling valve in Landsat 7, are covered with MLI structures that provide a box-like shape over the items, in which blanketing is not secured directly to critical interfaces,

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Fig. 1. Left: Conventional teleoperation keyboard and GUI (KB); Center: da Vinci master console (dV) with space mouse; Right: remote robot with satellite (see Fig. 2 for closeup of cutting assembly). Left image shows NASA operator performing trial with augmented virtuality (AV) visualization on 3D monitor (lower left monitor). Operator is wearing noise-canceling headphones and 3D shutter glasses. Conventional (CAM) visualization is similar, except that lower left monitor shows 2D camera image. Lower right monitor shows robot control GUI (also shown in Fig. 4).

but only to the exterior panels around it. These free-standing MLI "hats" (see Fig. 1-right) present a unique challenge for robotic systems to remove.

During ground-based testing, experienced operators at SSPD have indicated that they rely heavily on the views provided by cameras mounted on the robot's end effector to inform their situational awareness (SA) and make real time decisions on robot commands. However, there are several factors that reduce a teleoperator's ability to utilize these camera views. In tight areas, these cameras often have limited visibility of the MLI being cut, as anticipated for the top segment of the cut path (green lines) in Fig. 3. In addition, remote teleoperation of in-space systems involves inherent limits on bandwidth that provide an upper bound on image quality and frame rate. Commands to, and telemetry from, remote systems are relayed through ground stations and often one or more communications satellites, introducing delays on the order of 2-7 seconds between sending a command and receiving telemetry of the robot's response. In controlled ground-based experiments, without telemetry delays, highly skilled telerobotic operators with years of experience may take in excess of one hour to completely cut and remove an MLI hat covering the satellite fuel valves. When the factors above are considered, this time can significantly increase.

III. System Description

The JHU laboratory testbed, shown in Fig. 1, employs a UR-10 robot manipulator (Universal Robots, Odense, Denmark), equipped with a rotary cutting tool (Fig. 2). The tool is composed of a 45 mm circular blade (Arteza, Wilmington DE) that is attached to a Dynamixel MX-12W servo motor (Robotis, Lake Forest, CA). The tool is mounted on a six axis force/torque sensor (JR3 Inc., Woodland, CA) that measures the forces applied on the blade. A BlackFly (FLIR Integrated Imaging Solutions Inc. BC, Canada) 1080p color camera is also mounted on the UR-10 end-effector to provide a close-up view of the blade and worksite. The lens of the camera is equipped with a LED ring light.

The testbed also includes one pan-tilt-zoom (PTZ) camera (HuddleCam Downingtown, PA) and one BlackFly deck camera equipped with a wide angle lens (Rochester, NY) as proxies for cameras to be mounted on the servicer spacecraft deck. Both of these cameras are attached near the base of the UR-10 and directed towards the MLI hat to provide SA views of the workspace, as shown in Fig. 1-right.

The master input device is either a keyboard (Fig. 1-left) or a haptic arm (Fig. 1-center), where the latter consists of the Master Tool Manipulator (MTM) of the da Vinci Research Kit (dVRK) [3]. The dVRK is an open source research platform based on the da Vinci surgical robot [2]. Details of the master consoles are given in the following section.

IV. System Configurations

The system supports several human-machine teleoperation interfaces, based on the type of visualization and method of teleoperation. The following sections present two different visualization interfaces: conventional camera view (CAM) and augmented virtuality (AV), and two different teleoperation interfaces: keyboard (KB) and da Vinci (dV), which lead to the three configurations tested in the experiments (i.e., all combinations except dV+CAM). We note that our prior work [9] demonstrated that dV+AV provided better teleoperation

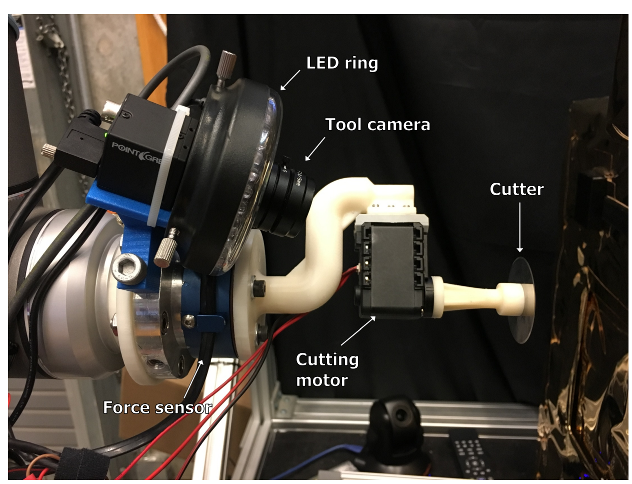

Fig. 2. Closeup of cutting assembly on UR10 robot.

performance than dV+CAM.

A. CAM: Conventional (Camera) Visualization

For visualization, GSFC's current teleoperation console provides a combination of video displays—real video and simulation—to guide operators while executing the robotic servicing tasks. The video feeds are captured from an array of SA cameras mounted on the deck of the servicing satellite and from the tool cameras that are designed to provide high quality close-up views of the robotic tools and their immediate surroundings. Although the GSFC console provides a 3D simulation of the on-orbit scene, the accuracy of the model is not expected to be high enough to support precision teleoperation. Thus, NASA robot operators are trained to rely primarily on the time-delayed video feeds streaming from the servicing satellite.

A similar visualization console was implemented at JHU. It also includes two ring overlays, similar to the ones shown in Fig. 3, except overlayed on the camera image. The yellow ring indicates the contemplated pose of the circular cutting blade; when using the keyboard interface, it is updated whenever the operator changes the desired position in a text input. The red ring indicates the commanded robot position [4] and immediately (i.e., without time delay) begins following the commanded trajectory when the operator initiates a motion. These overlays are not present in GSFC's current system, but could easily be added because they require only the camera intrinsic and extrinsic (hand-eye) calibration.

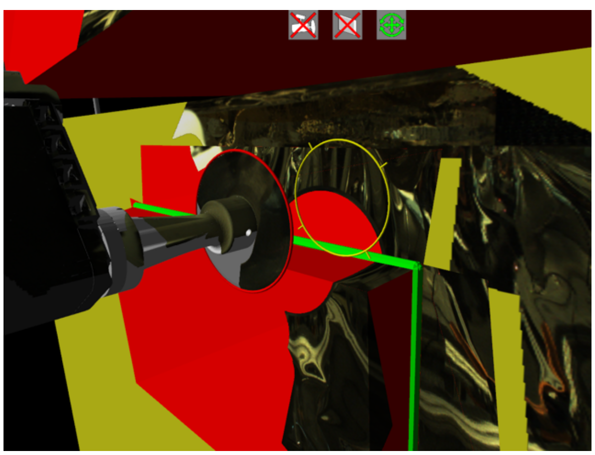

Fig. 3. Augmented virtuality (AV) visualization of virtual 3D model, augmented by projection of real tool camera image. 3D model includes satellite CAD model (yellow), reconstructed MLI hat (red), and robotic tool. Overlays include commanded robot position (red ring), contemplated robot position (yellow ring), and cut path (green lines).

B. AV: Augmented Virtuality Visualization

The augmented virtuality visualization is based on our prior work, where we first perform a robotic image survey and then register the 2D survey images to a 3D CAD model of the satellite [8] and reconstruct features, such as the MLI hat, for which there are no accurate pre-existing models [9]. The resulting 3D model, which includes both the registered satellite CAD model and the reconstructed features, can be visualized (in stereo) from arbitrary viewpoints. Other researchers have noted that virtual displays can provide alternative views that could not be achieved with live video [4]. This approach also enables the operator to define a desired cut path with respect to the model. We go beyond virtual reality by projecting the time-delayed video captured from the tool and/or SA cameras onto the 3D model to create an augmented virtuality visualization.

In the present study, we employ an improved version of the visualization system (see Fig. 3) that addresses rendering flaws encountered in the previous version and implements new visualization features. Due to performance concerns and feature limitations, the new renderer software does not rely on RViz and was instead re-implemented in C++, using OpenGL.

The new renderer performs real-time ray-tracing to project the camera images with correct occlusions on the 3D scene, thereby mapping the image of the tool assembly on the tool model and the image of the satellite on the satellite model, without the need of an image mask. The 3D models in the scene are all wrapped in high resolution texture, and the renderer is capable of adding multiple camera projections to the texture using mosaicking techniques to cover the visible parts of the satellite model with registered real-life camera images. On top of the static mosaic, the system also maps on the scene the time-delayed video streams captured from the cameras. All this is performed real-time, enabling a more realistic and dynamic 3D visualization.

The new renderer also enables the display of a variety of status indicators in the 3D view. The indicators are rendered as icons and text overlays (see icons at top of Fig. 3). The robot model in Fig. 3 is updated by the delayed telemetry from the remote robot. In addition, Fig. 3 shows the yellow and red ring overlays that were described in Section IV-A and are available in both CAM and AV modes.

C. KB: Conventional (Keyboard/GUI) Control Interface

For telerobotic control, NASA has significant experience with interfaces such as keyboards and joysticks and tends to favor keyboard interfaces for high risk operations, such as those where the robot is in contact with its environment. We created a keyboard/GUI interface for the experiments at JHU that closely replicates the interface used at GSFC. This interface, shown in Fig. 4, allows operators to input a relative (*delta*) or absolute (*final*) goal pose in Cartesian space (with respect to a specified reference frame), preview the expected result, and execute the command after confirming desired motion. In all configurations, the reference frame can be set to the robot's (stationary) base frame or the tool frame. When using the augmented virtuality interface, a task frame can also be selected to enter commands relative to the desired cut path. The task frame is not available in the conventional interface because it requires an accurate registration between the robot and the satellite, which is not normally available.

As the operator adjusts the GUI, the visualization displays a preview of the commanded pose via the yellow ring described in Section IV-B. When the operator is satisfied with the command, the *Move* button initiates the motion. During

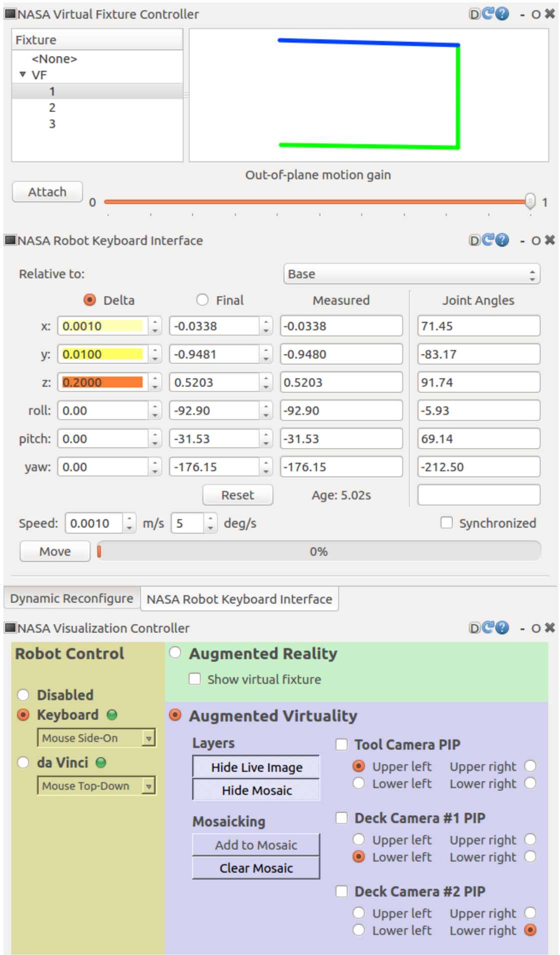

Fig. 4. Conventional robot interface GUI

motion, the preview ring remains stationary, allowing the operator to judge the progress towards the goal. Once a motion reaches its goal or is aborted, the preview ring resumes tracking the current value of the inputs.

D. dV: da Vinci Control Interface

The da Vinci interface (Fig. 1-center) allows the operator to directly teleoperate the satellite servicing robot. The operator holds one of the two MTMs, looks into the stereo viewer, operates the six foot pedals, and optionally uses the space mouse. The da Vinci teleoperation interface extends on the previously reported system [9] with new features and improvements. A gripper pinch gesture replaces the foot pedal as the command to start moving the space-side robot. New foot pedal interactions allow switching to rotation- and translation-only modes and repositioning the virtual camera using the da Vinci MTM.

As with the traditional teleoperation interface, the desired cut path is displayed in the visualizer. Operators may opt to use it solely as a visual guide. However, the da Vinci interface also offers the ability to use the desired cut path as a virtual fixture, with non-isotropic gains and haptic feedback. The haptic feedback replaces the force gradient used in the previous system. When the virtual fixture is enabled, a force or torque is applied in the translational and rotational directions outside of the desired cut plane that gently pushes the manipulator back into the desired plane. A slider in the GUI allows the operator to scale down the velocity in the directions orthogonal to the virtual fixture plane, ranging from the default scale factor of 1 (no scaling) to 0 (disallow motion completely, i.e., a hard virtual fixture). The system also provides an "auto-align" feature, enabled by pressing a foot pedal, which automatically moves the robot to align the end effector with the virtual fixture, first in rotation and then in translation.

V. Experiments

We evaluated three distinct system configurations to separately determine the effect of the augmented virtuality (AV) visualization and the direct telemanipulation (dV) interface. The following sections describe the subject population for the study, the experimental setup, and the three system configurations.

A. Study Subjects

The study used NASA robotic teleoperators, who go through extensive training to learn the intricacies of remotely controlling on-orbit robot arms. SSPD's training process, which is modeled on that used for robot operators at Johnson Space Center, requires potential operators to become familiar with robotic operations and robot kinematics. New teleoperators begin by observing ground based testing and acting as a safety operator with an emergency stop button. Next, they are introduced to robot operations using SSPD's smaller industrial robots, and are gradually introduced to the more advanced concepts required to perform any contact operations. Teleoperators for flight systems must then train on the ground unit of the flight robot. In addition to training on the robotic system, teleoperators also train for a given task by first using SSPD's ground industrial robots before performing the task on the ground unit of the flight robot. This progression ensures that teleoperators for servicing missions are experts in both the robotic system they are operating as well as the task they are performing.

B. Experimental Setup

The experimental setup consists of a control station and a servicing platform, as shown in Fig. 1. The control station is either a keyboard and computer displays (KB) or the da Vinci master console (dV), as described in Section IV.

The mock satellite is constructed from 80/20 aluminum bars and panels wrapped in a layer of Mylar [8]. Not including its solar panel, the satellite is a box of size $24 \times 24 \times 36$ inches. MLI hats were manually assembled to replicate the space-grade hat of Landsat 7 at a reasonable cost. The blanket used for the hats is composed of 21 alternating layers of 0.5 mil (0.013 mm) polymer film (McMaster 8567K102) and fine tulle. The layers are then placed between two layers of 1 mil (0.025 mm) metalized PET (Mylar) film (CS Hyde 48-1F-1M). Kapton tape (McMaster 7648A34) is used to assemble the blanket and to fold the corners of the hats

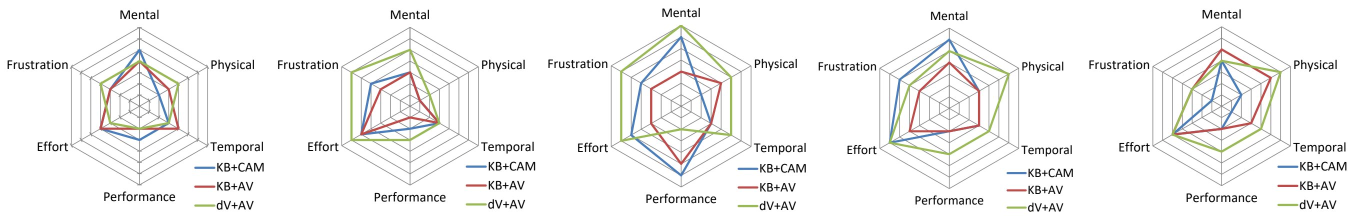

Fig. 5. TLX survey results for Subjects 1-5 (left to right). Values range from 1 to 7, with 7 representing the greatest burden in that category.

following NASA specifications. The fabrication of each hat takes approximately 3 hours for a trained person. Because the MLI is folded multiple times at the corners, the cutting blade must cut through approximately 100 layers of film, tulle, and tape at the thickest point.

The initial preparation consists of first calibrating the camera intrinsics and extrinsics, and then performing a robot-to-satellite registration, as described in [8]. Specifically, the robot acquires a set of 2D images from multiple poses, which are then registered to a 3D model of the rigid parts of the mock satellite. The resulting camera calibration and robot-to-satellite registration are used for all trials. Before each trial, a new hat is mounted in approximately the same location on the satellite. An image survey is performed, using predefined viewing angles, to manually reconstruct the hat's geometry, as described in [9]. A desired cut path is defined in the same relative location on each reconstructed hat model. Each trial begins with the robot in the same position relative to the mock satellite.

During trials, operators sat out of visual range of the robot, relying only on the time-delayed camera feedback for visualization. In addition, all operators wore noise-canceling headphones, through which music or white noise was played, to prevent them from hearing real-time (i.e., undelayed) audio feedback, such as changes in the cutting motor sound. Figure 1-left shows an image from one trial. Operators completed a NASA TLX survey after each trial and a post-experiment survey after the last trial. The survey asked them to rate the difficulty of use for each system configuration and provided an opportunity for free-form feedback.

The order of trials was fixed to introduce no more than one new feature at a time. Each GSFC operator first performed the conventional (KB+CAM) trial, which emulates their familiar teleoperation interface, though with different hardware and software. Next, the augmented virtuality (AV) visualization was introduced, while keeping the familiar keyboard teleoperation interface (KB+AV). Finally, the AV visualization was kept and the da Vinci teleoperation interface was introduced (dV+AV). Operators were allowed to practice with each configuration prior to beginning each trial.

C. Conventional Teleoperation (KB+CAM)

The first experimental condition was designed to replicate the conventional visualization and teleoperation interfaces that are already in use at NASA. The visualization was used in Augmented Reality mode, using the stereo display as a 2D monitor. The red "commanded" and yellow "preview" rings were overlayed on the tool camera image. Operators were free to enable picture-in-picture overlays of the deck cameras or to display the deck cameras on a second monitor. The robot was controlled using the traditional robot interface with the ability to control in task frame disabled, reflecting the fact that the conventional system does not provide a sufficiently accurate robot-to-satellite registration to define a task frame.

D. Conventional Teleoperation with Augmented Virtuality (KB+AV)

The second experimental condition was designed to measure the effect of the augmented virtuality visualization. The visualizer was used in Augmented Virtuality mode on the 3D monitor, as shown in Fig. 1-left. The "commanded" and "preview" rings and the desired cut path were displayed in the virtual environment. Operators were able to move the virtual camera with the space mouse or use buttons on the space mouse to cycle between predefined views. An additional GUI element allowed operators to select one of the three segments of the cut path to define the task frame. Operators used the conventional robot interface, but with the task frame enabled.

E. da Vinci Teleoperation with Augmented Virtuality (dV+AV)

The final experimental condition was designed to measure the effect of the da Vinci teleoperation interface. The visualizer was used in Augmented Virtuality mode viewed through the da Vinci master console's stereo viewer. In addition to all elements from the previous experimental condition, the visualizer displayed icons to communicate the current internal state of the da Vinci robot interface. Operators were able to move the virtual camera using the space mouse or the da Vinci MTMs. On request from the operator, an experimenter operated GUI controls which are not currently exposed to the da Vinci interface, such as selecting and attaching to desired cut paths. Ultimately, these controls would either be implemented within the da Vinci interface or managed by a second robot operator.

VI. Results

There currently are five trained robot operators at NASA GSFC and all of them (100% of the target population) completed the experiments with all three configurations.

Figure 5 shows the results of the NASA TLX survey completed by each participant after each trial. It indicates that the augmented virtuality interface caused less stress (frustration) than the conventional visualization for three operators, a better self-assessed performance for three operators, and that all operators found it less or equally as difficult. Three out of five operators found the da Vinci teleoperation interface considerably more frustrating than either trial with the keyboard interface, and four operators thought it was more or equally as difficult. This is not surprising, given that it is an unfamiliar interface for these operators. This was also evident in the post-experiment survey, Table I, where operators rated the difficulty of each system configuration on a scale from 1 (very easy) to 5 (very hard). All five operators selected the KB+AV configuration as the easiest or as one of the easiest and four operators rated the dV+AV configuration as the hardest.

TABLE I
POST-EXPERIMENT SURVEY RESULTS (1 = VERY EASY, 5 = VERY HARD)

Condition	Op-1	Op-2	Op-3	Op-4	Op-5	Mean
KB + CAM	4	3	3	3	3	3.2
KB + AV	3	2	2	2	3	2.4
dV + AV	3	4	5	4	4	4.0

In order to evaluate success of the cut, the total number of layers and successfully-cut layers were measured. Figure 6 shows the number of layers cut compared to the number of layers present. Note that the geometry of the hat construction causes a significant increase in the number of layers that must be cut at a corner. Table II shows the rate of success and the degree of failure in terms of the number of layers cut. NASA has determined that the cut is likely to be successful if either all layers are cut, or if only the innermost MLI layer (X=1) is not cut in a short segment. The exact degree of success depends on the location of the cutting failure, the condition of MLI materials, and other factors; thus, they are determined on a case-by-case basis. We see that the KB+AV configuration led to the highest percentage of complete and acceptable cuts. The results also indicate that, despite the increased number of layers, the corners typically saw more success than the straight sides. We attribute this to the additional structural integrity of the hat, which restricts the layers from spreading apart as much as on the sides.

TABLE II
MLI CUTTING SUCCESS RATE

Layers not cut	KB+CAM	KB+AV	dV+AV
All cut	95.29%	99.71%	91.18%
X=1	0.00%	0.00%	0.59%
3≥X>1	0.59%	0.29%	1.76%
10≥X>3	2.35%	0.00%	3.24%
X>10	1.76%	0.00%	3.24%

VII. DISCUSSION AND CONCLUSIONS

We developed an augmented virtuality interface to support ground-based teleoperation of robots on orbit for satellite servicing tasks, subject to communication delays of several seconds and challenging visualization of the remote scene. The system was tested with trained NASA robot operators and the results indicate that the augmented virtuality visualization can provide benefits, including reduced execution time and lower task load, compared to the conventional visualization. One likely explanation is that the augmented virtuality system provides teleoperators the ability to choose arbitrary views of the robot workspace, which can significantly improve their situational awareness. This reduces risk and makes teleoperated servicing tasks more efficient and reliable. Although satellite servicing resembles telesurgery, our experiments also revealed that the NASA operators preferred the conventional keyboard/GUI interface over the da Vinci master console. This is likely due to their extensive training and familiarity with that interface, but also to the nature of the MLI cutting task, where most motions can be easily expressed within the task frame. The da Vinci master console might be more effective for other tasks, especially those involving complex motions that cannot be as easily commanded via a keyboard.

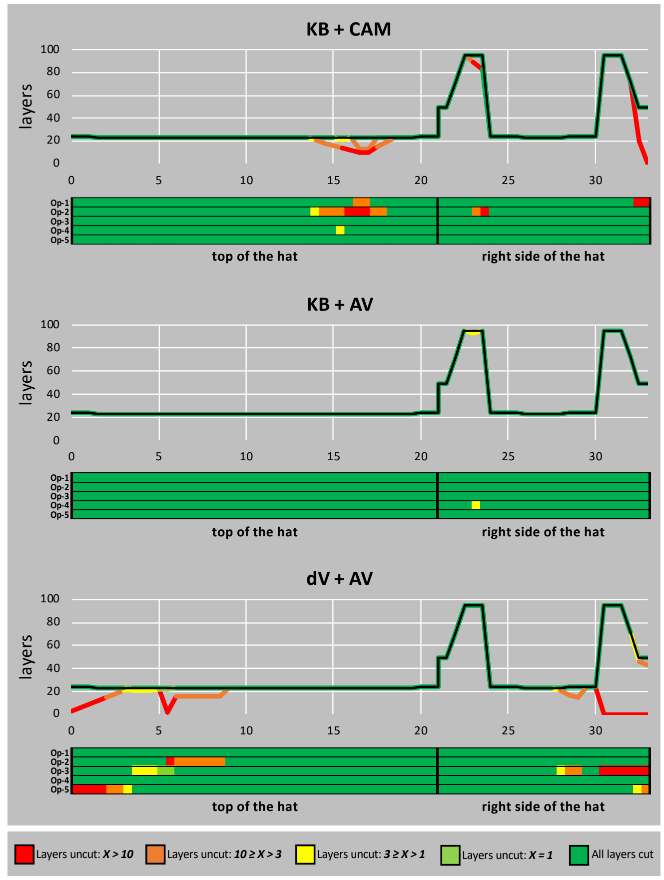

Fig. 6. Visualization of the number of layers successfully cut in all MLI cutting trials. Horizontal axis represents cutting progress [cm], starting at the top of the hat then continuing on the right side. The thin black lines indicate the number of layers that need to be cut, and the thick colored lines show the number of successfully cut layers for each trial. A single sheet of MLI consists of 23 layers, but there are as many as 95 layers at the corners where the MLI is folded and taped multiple times. The colored horizontal bands under the charts show the number of layers cut for each trial. There are 5 bands for each task, representing the 5 operators.

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