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Human Interfaces For Robotic Satellite Servicing

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ABSTRACT

On-orbit servicing (OOS) is growing in importance for the sustainment of certain satellite systems. Although it is more economical to replace satellites in many cases, OOS could be beneficial or even critical for more expensive satellites such as Space-Based Laser and constellations such as the Global Positioning System. Some future OOS missions including refueling and modular component replacement will be highly autonomous, but there will still be a need for humans to supervise and to recover when unexpected situations arise. Non-routine tasks such as damage repair or optics cleaning will likely require a more significant level of human control. The human interfaces for such activities can include body tracking systems; three-dimensional audio and video; tactile feedback devices; and others. This paper will provide some insights into when and at what level human interaction may be needed for OOS tasks. Example missions will be discussed and the argument will be made that human interfaces are important even for primarily autonomous missions. Finally some current research efforts within NASA, academia and the military will be discussed including research being conducted in the Human Sensory Feedback Laboratory at Wright-Patterson Air Force Base.

1. INTRODUCTION

To date, the National Aeronautics & Space Administration (NASA) has relied extensively on astronauts to perform maintenance and repair tasks in space. Indeed humans provide flexibility and ingenuity that is not yet possible even with the smartest robot and often this adaptability has been critical for on-orbit servicing (OOS) tasks. Sending humans into space, however, requires expensive life support systems and poses a risk of injury or death.[15] Thus plans for future Air Force OOS missions do not call for humans in space. The Defense Advanced Research Projects Agency's (DARPA) Orbital Express program, for example, is striving to perform basic servicing tasks autonomously.

Human interaction, however, will likely still be needed for future OOS missions at least in a supervisory role. Since lower cost satellites are usually not cost effective to service, OOS will typically be performed on the most expensive or critical satellites, thus the stakes will simply be too high to blindly trust an autonomous system in such a complex activity. Should something go wrong during the docking or servicing, supervisory controls can possibly prevent serious damage to these valuable assets. Software errors, incorrect sensor calibration, solar weather, and space debris are just a few of surprises to be contented with during a mission. Such robustness is quite difficult or cost prohibitive to automate.

Through research in uninhabited vehicles, the military understands the importance of being able to control autonomous entities. It is arduous and costly to develop software that is flexible enough to deal with all possible situations that can arise, thus supervisory controls are available on most autonomous systems. But basic human computer interfaces have often turned out to be inadequate in certain situations. Interfaces, including displays (visual, auditory and tactile) and control mechanisms, need to be carefully designed to ensure that the human is able to effectively react within the time constrains.

Many questions need to be answered in developing human interfaces for on-orbit servicing. Will a monitor, keyboard and mouse suffice to prevent a mishap should the human need to take over? If so, how should the display be laid out? How should color and graphics be used? Are more advanced control devices needed? Can performance be enhanced by using computer-generated images superimposed onto live images (augmented reality discussed later)? To answer these questions a designer may want to match the control requirements with the human's capabilities and limitations, but this is often not done.

For tasks that require adaptability like damage repair it seems likely that humans will have an even more significant role for the foreseeable future. Tele-operation of robots will allow many tasks normally performed by astronauts to be performed by humans on Earth. However it is critical to determine how much situational awareness and what type of control mechanisms are best for the task. Devices typically used for virtual reality such as head-mounted displays and body trackers have been successfully employed on a NASDA (the Japanese space agency) Engineering Test Satellite (ETS-VII) OOS test mission. It is widely agreed, however, that more research is needed before we can be confident in our ability to perform OOS tasks remotely. Task performance can be improved by employing autonomy for certain aspects (such as grasping objects with acceptable force) but it is not clear how these issues should affect the human interfaces.

2. SUPERVISORY CONTROL

By strict definition, an autonomous system is void of human involvement. However the reality is that systems we consider autonomous usually provide some human oversight. The control may be limited to aborting a whole mission or aborting singles steps, or the human may be allowed to pick from a menu of suggested actions. It may be necessary with some systems to allow the supervisor to take over operation manually if the automation is unable to handle the remainder of the task. In any case, some control is usually deemed necessary if the task is considered at all complex, uncertain and/or critical. Table 1 taken from Sheridan 1992 shows the ten levels of automation and it should be noted that all but level 10 require some degree of human involvement.[10] Since level 10 is rarely achieved, human interfaces must be considered for nearly all systems.[7]

Table 1: Levels of Automation

Level		Action performed by the computer. The computer…
HIGH	10.	Decides everything and acts without human involvement
	9.	Informs the human only if it, the computer, decides to
	8.	Informs the human only if asked to
	7.	Executes automatically then must inform the human
	6.	Allows the human a restricted time to veto before automatic execution
	5.	Executes the suggestion if human approves
	4.	Suggests one alternative
	3.	Narrows selection down to a few
	2.	Offers a complete set of alternatives
LOW	1.	Offers no assistance: human makes all decisions and performs all actions

In supervising autonomous systems, it is not only important to identify what controls will be provided to the human but the interfaces need to center around the capabilities of the human. For example if actions are rarely required of the human, the designer must develop a method to alert the user without undue anxiety. Once they are alerted, the user may need to rapidly gain situational awareness in order to react appropriately. Thus bright flashing lights and sirens may not be the most effective method to alert a supervisor of a problem.

2.1 Experiences with other autonomous systems

The Air Force is trying to automate some functions that have typically been performed by humans – even piloting aircraft.[12] As is to be expected, there have been some hard lessons to learn in the development of such systems. One of these lessons occurred on March 29, 1999 when a Global Hawk Unmanned Aerial Vehicle (UAV, Figure **1**) crashed at the South Range of China Lake Naval Weapons Center, California. The mishap occurred when the highly autonomous UAV inadvertently received a test signal for flight termination from a test range on Nellis Air Force Base, Nevada, which was outside the frequency coordination zone in which the UAV's mission was being flown. This caused the UAV to go into a termination maneuver involving a pre-programmed, rolling, and vertical descent from an altitude of 41,000 feet.[1]

Figure 1: Global Hawk Unmanned Aerial Vehicle

One of the conclusions of the accident investigation was that the ground controller lacked the ability to override the termination signal. The controllers on duty during this incident indicated that there would have been sufficient time to override the termination signal if they would have had the ability to do so.[13]

In another incident on April 18, 1999, an RQ-1 Predator UAV crashed near Tuzla Air Base, Bosnia as a result of both mechanical problems and human factors. The Predator was returning from a reconnaissance mission over Kosovo in support of Operation Allied Force. According to the accident investigation board report prepared by Air Combat Command officials, the Predator experienced a fuel problem during its descent into Tuzla.

The two Predator pilots, who controlled the aircraft from a ground station, executed critical action procedures but were unable to land the aircraft safely. According to the report, the pilots became too focused on flying the aircraft in icing and weather conditions they had rarely encountered. In addition a lack of communication between the two pilots during the flight emergency was cited as a cause of the accident.[2]

2.2 Relating to autonomous satellite servicing

Similar incidents can be envisioned in the performance of an on-orbit servicing mission. If the servicer received an unexpected signal from another satellite or if the servicer collides with space debris, the target satellite could get damaged, ruined or put into an undesired spin. Even with supervisory control such events can occur, but based on previous experiences, such measures could mitigate the risk.

These risk reducing measures could be important for missions like those anticipated for the U.S. Defense Advanced Research Projects Agency's (DARPA) Orbital Express. The first mission for this program is slated to demonstrate the ability to transfer fuel between two satellites. In a possible follow-on mission, refueling may be carried out on the Space Based Laser Integrated Flight Experiment, which is scheduled for launch in 2012 and testing the following year.[11]

3. FUTURE OF TELEOPERATION FOR SERVICING

Although it is considered highly desirable to automate most servicing tasks, human control is advantageous for certain tasks. Some tasks – such as repairs or workarounds – may be unique, unpredictable or simply too expensive to automate.[15] Teleoperation may be the best option in these cases.

3.1 Applying new interface technologies

Performing on-orbit servicing tasks from a ground station is challenging for several reasons. Obviously a person will not have the same level of situational awareness or dexterity as they would when performing ground-based maintenance with their bare hands. However stereoscopic displays – visual and auditory – and haptic feedback – touch and force – can make up for some of the loss in situational awareness.

Another significant challenge is telemetry delays of an estimated 2 to 5 seconds usually make it necessary to work in discrete steps. Predictive displays have been shown to ease these delay effects by Massachusetts Institute of Technology, NASA Jet Propulsion Laboratory and others.[15]

Virtual and augmented reality technologies may revolutionize the ability to perform remote servicing. Body tracking devices, head-mounted displays, haptic feedback devices and three-dimensional audio are among the technologies that can be employed. The Air Force Research Laboratory, The Ohio State University, Wright State University and Air Force Institute of Technology plan (in 2002) to explore the utility of a virtual reality room called the Cave Automated Virtual Reality Environment (CAVE) for servicing activity.[4]

Remote servicing is also well suited for the application of augment reality in which computer-generated information is superimposed on the real-world view. Since the precise location of the cameras can be tracked with respect to the satellite being serviced, it theoretically possible to align the superimposed images with the real-world views. Thus the scene can be annotated with instructions, part labels, virtual x-rays or other task guides.[3] This capability can also be used with predictive displays where annotations are superimposed over virtual images rather than real images.

3.2 Ranger program

The Space Systems Laboratory at the University of Maryland in cooperation with NASA has been designing Ranger, a new class of highly capable space robot. Ranger is designed to have the ability to perform many required operational tasks including on-orbit refueling, instrumentation package replacement, and deployment of failed mechanisms such as antennae and solar arrays. Ranger has been designed to be a general-purpose servicing vehicle, capable of approaching a wide variety of tasks.[6]

Ranger was designed to have force and reach capabilities similar to those of an astronaut in a space suit. Ranger has four manipulators. These are attached to the manipulator module, which is a 12-inch cubical structure at the front of the robot. Ranger has two dexterous manipulators, a video manipulator and a positioning leg. Two dexterous arms enable cooperative manipulation, or one arm can be used to help stiffen the dock to the work site when large forces are required. A video manipulator, in conjunction with wrist and boresight cameras, help provide the wide range of views necessary when considering a wide range of tasks. Finally, a positioning leg allows the vehicle to be repositioned with respect to the work site, which is important because of the natural workspace limitations of the dexterous manipulators.

The first on-orbit demonstration of a Ranger vehicle is scheduled for 2003 when the Ranger Telerobotic Shuttle Experiment (TSX, Figure 2) will fly on the Space Shuttle. Ranger TSX is designed to blur the line of distinction between human and robotic OOS operations by demonstrating the ability of a space robot to perform some tasks originally designed for human EVA subjects, along with tasks designed specifically for robots. One type of task that Ranger TSX will perform is Orbital Replacement Unit (ORU) removal and installation. ORUs, typically some form of replaceable electronics module, have often been used in the past in human extra-vehicular activity (EVA) operations, and are also planned for use in future robotic operations. Robotic ORUs have special fixtures and releases designed for a robot to grasp and actuate.[9]

A portion of the Ranger TSX mission will be to demonstrate the removal and installation of human EVA and robotic ORUs. A task board launched with Ranger TSX will include a Hubble Space Telescope (HST) Electronics Control Unit (ECU) ORU, which was designed for human servicing, and a Remote Power Control Module (RPCM), which is an external component of the International Space Station, designed to be serviced by robots. Ranger TSX will approach these tasks using methods similar to those employed by human EVA subjects. A major difference is that instead of grasping EVA tools by hand, Ranger will use a set of interchangeable robotic end effectors such as a bare bolt driver, a right angle bolt driver, an end effector designed for grasping a microconical robotic interface, and various grippers. The robot will be teleoperated by a human pilot from the aft flight deck, or from a ground station. The end effectors may be autonomously interchanged at the command of the pilot.

Figure 2: Ranger TSX

The first Ranger vehicle (the predecessor of Ranger TSX) is the Ranger Neutral Buoyancy Vehicle (NBV, Figure 3). Ranger NBV, designed for operation in the weightless environment created underwater using neutral buoyancy simulation, has a similar robotics package to Ranger TSX, however it also contains a full propulsion module. By combining current robotic technology with a free-flying spacecraft bus, Ranger embodies a new class of self-contained OOS vehicles that will help meet the demand for future space operations.[5]

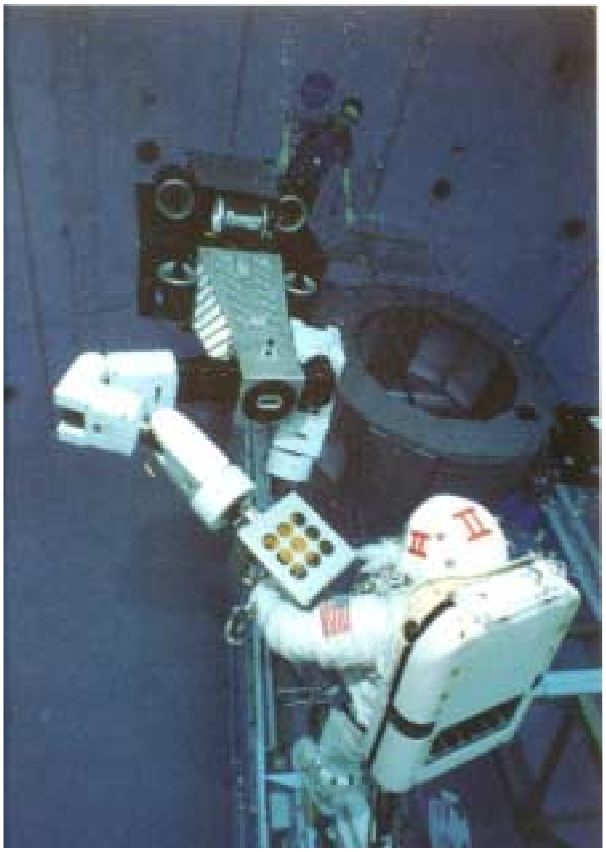

Figure 3: Ranger NBV

Ranger NBV, operational since its rollout in late 1994, has successfully performed a significant number of realistic tasks, some unassisted, and some in cooperation with suited EVA subjects. An extensive range of experience has been gained in both free-flying and attached servicing operations.

When in free-flight, it is often difficult to determine the location of Ranger with respect to the surrounding environment. Boresight cameras cover only a limited field of view, and offer no information about objects to the sides of the vehicle. This information is critical when maneuvering the vehicle in tight spaces in the case that a well-defined docking target is not visible. Typically, in this case, an additional view is desirable. This can be provided by the video manipulator or an external source such as cameras mounted on the target vehicle.

When working with robotic manipulators, the cameras and the operator are often focused almost exclusively on the end effector being controlled. In a multi-armed vehicle, it is important to also be aware of the overall configuration of the manipulators with respect to the vehicle and each other. This is important for effectively utilizing the workspace of the manipulators, avoiding singularities, and also for avoiding collisions between manipulators, and with the vehicle itself. This information is provided to the Ranger NBV pilot by using the joint angles that are passed back from the vehicle to create a computer generated representation of the vehicle and the manipulators.

Additionally, when working with manipulators, a single camera view of the task environment has proven to be rather inadequate for many tasks. It is often significantly difficult with only one camera to determine the distance between the task and the end effector, or the attitude of the end effector with respect to the task. It is often helpful to use a stereo pair of cameras along with some form of stereo display to help determine the distance between various objects in the task environment. The two forms of stereo display used by Ranger NBV are head mounted 'virtual reality' style helmets, or alternately, Liquid Crystal Display (LCD) glasses used in conjunction with a stereo interlaced video monitor. Even more helpful is the inclusion of an orthogonal view of the end effector. Clear and controllable views of the task environment are also very important in handling unexpected anomalies. Occasionally, the task hardware does not behave as expected, and a clear view of the environment with the ability to inspect from various angles has proven to be invaluable for anomaly resolution.

Over its years of operation, Ranger NBV has replaced ORUs, removed and attached electrical connectors, assembled structures, opened access doors, removed fasteners, walked "hand over hand" on EVA handrails, and interacted with EVA subjects, both from the end of the remote manipulator system, and from free-flight. This experience has clearly demonstrated the capability of a trained pilot teleoperating a highly capable dexterous robotic vehicle to accomplish a wide variety of tasks under a wide range of conditions.

3.3 Human Sensory Feedback Laboratory

At the HSF (Human Sensory Feedback) Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio, an ongoing research effort involves the investigation of issues related to a cleaning task with a space-based laser. The ultimate goal in this simulation is to incorporate as much autonomy as possible, but allow the human to intervene if an unplanned emergency should occur. Some of the first issues under consideration are the control of such a system in the presence of time delays, which typically occurs when the task is at a very distance location. For the initial study, humans control the cleaning or maintenance operation at the space based laser from an outlying location and are given three display conditions with three levels of time delays. Figure 4 illustrates the basics of the concept of interest. The three display conditions presented to the human operator are a direct view, a dual camera-viewing scenario, and a virtual reality display (Figure 5).

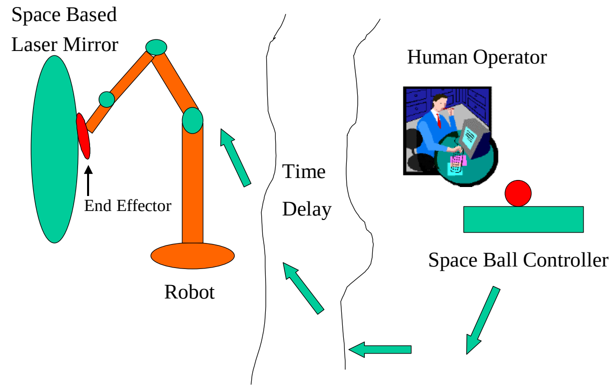

Figure 4: The Space-Based Laser cleaning simulation

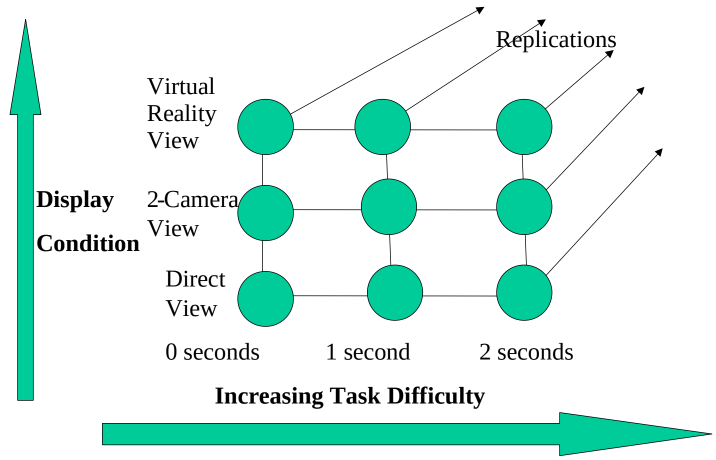

Figure 5: Experimental design conditions for initial study

The three levels of time delay are zero seconds, a one-second delay and two seconds of time delay. The primary objective of this study is to see if an improved display condition could enhance operator performance of the mirror cleaning task, even in the presence of large time delays.

Certain important performance measures will evaluate the efficacy of the different display conditions. The performance measures include: the time to complete the task, minimizing the force interaction of the robotic system with the mirror during contact, and a measure of the accuracy of the movement commands produced. As mentioned earlier, autonomy is an important consideration in the design of this complex system. By incorporating more and more levels of autonomy (intelligence) at the end-effector, it is desired to demonstrate better performance, especially when the time delays heighten and there is increased uncertainty in the operating environment. The ultimate goal will be maximum autonomy at the end-effector, but with the requirement that a human can enter the system in the event that mission-critical events occur that were not planned. Figure 6 illustrates the spaced-based laser mirror being contacted by a Puma-260-like robot in the HSF Laboratory. Figure 7 illustrates an operator working in the direct view mode.

Figure 6: Puma-like robot simulating cleaning task

Figure 7: Operator in direct view operating condition

Figure 8 portrays another operator with the camera and virtual reality view. The operator manipulates a "space ball" controller (figure 9) that provides 6 degrees of freedom (three translations and three rotations). The present level of autonomy (or intelligence) at the end-effector uses the concept of "force accommodation." This autonomy methodology means that a local loop is running continuously and maintains the end-effector perpendicular to the mirror at all times (independent of any inputs from the human). This type of autonomy at the end-effector also maintains and regulates a constant force contact during the cleaning operation. Local intelligence is thus provided and an efficient means of performing the task is accomplished. This procedure also unloads any commands from the human necessary to provide both proper contact orientation and regulation of constant contact force. Thus the human has his workload reduced and the autonomy introduced at the end-effector has been productive in the mission of cleaning the mirror.

Figure 8: Operator with virtual reality and dual camera views

Figure 9: The Space Ball Controller by Force Sensor

The initial study in the HSF Laboratory is concerned with which type of display condition may be beneficial to the operator who has to function in environments where large time delays may occur. Figure 10 is a close up view of the virtual reality display. This is a predictive display, in that it provides to the operator an extrapolation of where the end-effector is headed. Both velocity and position predictions are added to this visual rendering in an effort to improve the operator's ability to perform the cleaning task when large delays may be present.

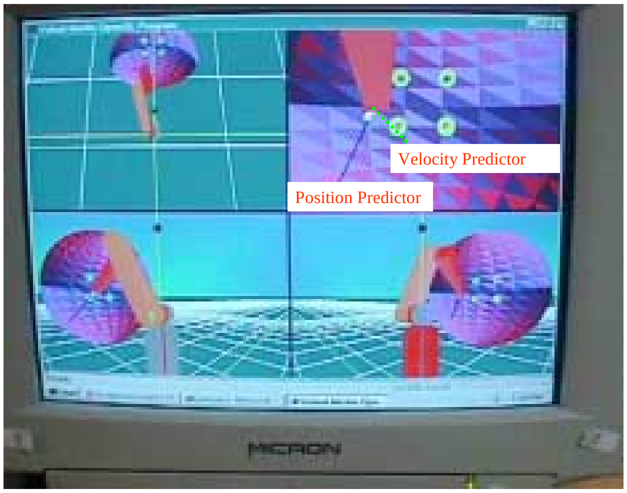

Figure 10: Multiple view display

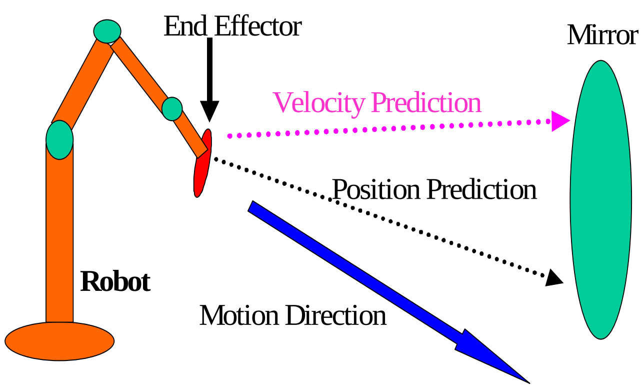

Figure 11: Method of rendering predictive display conditions

In Figure 11, a description of how the prediction is rendered is portrayed. The velocity of the end-effector is represented as the pink line; the predicted position of the end-effector is displayed as the black line. By dynamically moving the robot (through the interaction with the space ball controller), the operator can sense a projection of his motion through the action it produces at the end-effector. The true measure of success is dependent on the performance measures obtained.

The goal of this initial study is to see if a certain display condition may be beneficial when the operator has to perform the cleaning task with time delays. We have compared preliminary performance data of the three display conditions (direct view, camera view and virtual reality view) for the three delay conditions (0, 1 and 2 seconds of time delay). The first performance metric considered is based on the time to complete the task. Early results indicate that the degradation of performance due to time delays seems mitigated by the addition of the predictive display condition.

5. CONCLUSIONS

Whether OOS activity is performed with teleoperation as on the Ranger or autonomously as planned for the Orbital Express program, the role of the human should not be an afterthought. Human factors needs to be a consideration throughout the system design process because these issues can impact many aspects of the system. Experience gained working with unmanned air vehicles has shown us that overconfidence in the ability to perform tasks autonomously can lead to disastrous consequences. Columns of numbers may provide useful information to the engineer who designed the system but when an emergency situation arises, more elaborate interfaces can mean the difference between success and failure.

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