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COSMOS: A VR-Based Proof-of-Concept Interface for Advanced Space Robot Control

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Abstract

Virtual reality (VR) technology enables new forms of control for robot operations. This paper describes a VR-based proof-of-concept user interface that has been developed to demonstrate new control techniques for the Space Station Remote Manipulator System. Those techniques aim at improving overall operation performance and safety by using the combined power of VR, predictive displays and direct manipulation.

Key words: Teleoperation, Telemanipulation, Human-Computer Interaction, Virtual Reality, Predictive Display, Supervisory Control

1. Introduction

Complex space robots such as the Space Station Remote Manipulator System (SSRMS) shown in Figure 1, would benefit from advanced user interfaces in order to reduce their complexity of operation. This would improve overall system efficiency by reducing operator learning time as well as operation time for most of the tasks. This, however, must not be done at the expense of safety of the system.

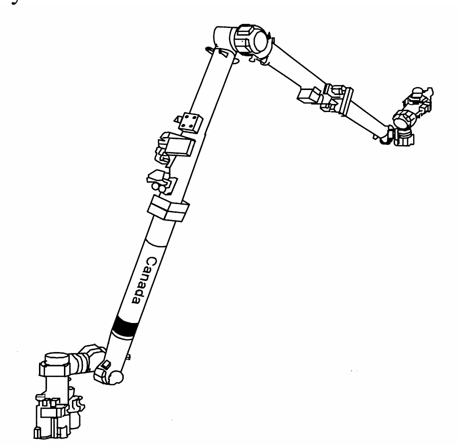

Fig. 1 The SSRMS robot arm

The use of VR can help to achieve these goals by offering the possibility of an infinite number of synthetic viewpoints. It can also offer simultaneously local and global views of the work site, therefore potentially increasing the situational awareness of the operator when compared to the standard, and limited, number of direct viewpoints and live video feeds [1, 2]. The existence of a model of the environment can also lead to new forms of control that are not currently possible, by providing predictive displays and a direct manipulation interface to the operator [3, 4].

The potential of VR in the robotics field has been assessed for training, mission planning, and on-line task execution [5, 6, 7]. In the SSRMS case, the usefulness of VR has already been demonstrated for training and mission planning purposes with systems such as MOTS and IVS [8, 9].

The SSRMS is currently operated by an astronaut located inside the International Space Station (ISS) and the operation can be divided in two non-exclusive phases:

1) Camera selection and control, to obtain views of the work site
2) Robot control, to reach the desired configuration

The usefulness of VR has already been shown for camera selection and control phase of SSRMS operation [10]. This paper analyzes the different design constraints and describes a proof-of-concept VR-based user interface that has been developed to demonstrate new robot control techniques for the SSRMS.

2. Context of the SSRMS Control

Before anything else, it is important to understand the role of the SSRMS as well as the current techniques used to control it.

The SSRMS is a 17.6 meter long, 7 degree-of-freedom (dof) robot arm made of rotational joints. It is used mainly for the assembly and maintenance of the ISS and is generally controlled with two 3 dof hand controllers using one of two classic operator-in-the-loop control techniques.

The first control technique, and the simplest one to implement, is called single joint rate control. With this technique, the operator controls the movement of each joint of a serial robot one at a time. This way of doing things is suitable for simple robot arms with only a few joints, but quickly becomes unmanageable as the number of joints increases. This is mainly due to the fact that the operator must figure out the required movement of each joint in order to obtain the desired movement of the end-effector. This requires the construction of a cognitive inverse kinematic model of the robot arm, a task that is increasingly difficult to achieve as the number of joints increases.

In order to simplify things and let the operator focus on the movement of the end-effector, another technique called coordinated rate control (also known as resolved motion rate control) has been developed [11]. Using this technique, the operator indicates the translation and rotation of a particular point of reference on the arm, usually located at the tip of the end effector. The translations are done along the cartesian axes while the rotations are done along the yaw-pitch-roll axes. This technique allows the operator to focus on the task itself (for example, moving the end-effector), rather than on the way to achieve it, by letting a computer determine and control the necessary joint movements through the help of a mathematical inverse kinematic model of the of the robot arm.

This second control technique reduces significantly the effort needed to control the end-effector since the operator doesn't have to figure out the inverse kinematic model of the robot arm. The gain is proportional to the number of joints to control, since, as explained before, the inverse kinematics model is getting more complex with the number of joints to control. As a result, the SSRMS operators, which are currently the astronauts on-board of the International Space Station (ISS), genrally rely on coordinated rate control to achieve their tasks.

In addition to the control techniques used, several other factors must be considered when designing a new control interface for the SSRMS. One of them is that improved operational efficiency should not be done at the expense of safety, since safety is the number one priority in space.

Another factor to consider is that, due to several design considerations, the SSRMS moves relatively slowly, with a typical end-effector speed of a few cm/s. At this speed, moving a payload over several meters can take several minutes. Since the SSRMS is currently controlled in an operator-in-the-loop way, the operator attention is continuously divided between control and supervision of SSRMS operations. As a result, the attention reserved to supervise the operations is reduced and thus increases safety risks, since part of operator's attention is dedicated to robot control instead of, for example, checking for possible collisions.

For a more detailed description of the SSRMS, its tasks, and control techniques, please refer to [12].

Given those considerations, it is desirable to opt for a more supervised form of control rather than the classic operator-in-the-loop control, which asks for long periods of concentrated efforts [13].

3. Previous Work

In order to alleviate the problem described in the previous section, several predictive displays have been proposed.

The first generation of those displays overlaid a real-time graphical simulation of the robot arm on a static image of the real work site to help the operator figure out the outcome of robot moves [14, 15]. Since it is limited to a single image of the work site, this technique is well suited for simple cases where the whole work site can be viewed from a single viewpoint. This is, however, not the case here, where the SSRMS can move everywhere on the large and complex structure of the ISS.

Advances in computing and displays technologies eventually led to another concept of predictive displays, where a virtual environment that replicates the real work site becomes the operator control interface [16, 17, 7]. This type of interface can also alleviate the operator from the effect of time delays that are either related to communication delays or slow robot motion, as it is the case here. Moreover, this kind of model-based interface is well suited to large and complex environment such as the ISS, since it can provide multiple synthetic views from any place in the virtual environment, not to mention the better control on lighting conditions. The use of a virtual environment also allows highlighting of specific items of interest in the virtual environment. All these possibilities, when used properly, can significantly increase the situational awareness of the operators.

4. The New SSRMS Control Interface

Operators often have to move the SSRMS end-effector or its attached payload to a particular pose (position and orientation).

In order to ease and improve SSRMS control, we implemented a VR-based proof-of concept user interface. This interface, called COSMOS, integrates three new control techniques for the SSRMS that take advantage of the VR-based control interface.

COSMOS runs on a dual processor computer using two 1.7 GHz Pentium 4, with 512 Mbytes of RAM.

It was developed in our laboratory, using the C++ programming language. Two 3 dof hand controllers are used, both for 3D navigation around the ISS and for controlling the SSRMS.

4.1 Predictive Pose Control

Using a 3D graphical model of the robot and its environment, the operator moves a virtual replica of the end-effector from its actual pose to the desired pose. The difference with the coordinated rate control interface here lies in the fact that the speed limit of the virtual-replica of the end-effector has been raised substantially, with a maximum speed limit of 1 m/s.

As for the traditional coordinated rate control, the computer does the rest of the work by computing the necessary joint moves to reach this desired configuration.

As a result, the operator doesn't have to continuously control the slow end-effector movement, and can instead focus all the attention on higher level supervisory tasks. By concentrating only on the supervision of the overall real operations, the operator provides a safety double check for possible collisions between parts of the real robot arm, its payload, and the surrounding environment.

This predictive pose control display is illustrated in Figure 2 below where the predictive display of the end-effector (in red) is moved to the desired pose. A 3D grid is coupled to the predictive end-effector to enhance its pose and motion perception by the operator. The system is controlled by the different axes of the hand controllers.

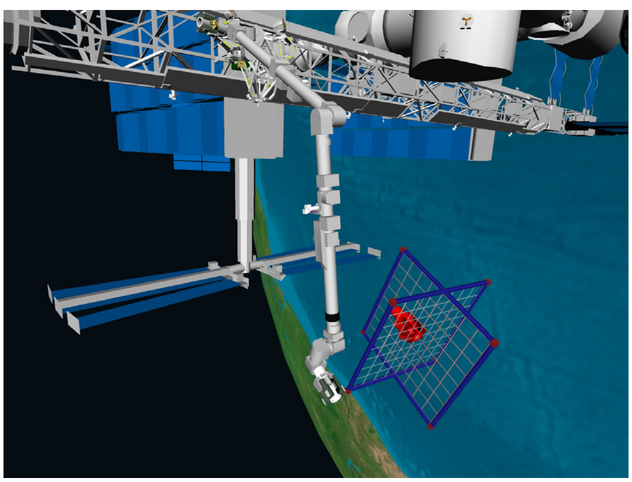

Fig. 2 Predictive pose control display

To indicate the out-of-range poses, a visual feedback is provided to the operator when the predictive end–effector goes into a pose that is not reachable by the SSRMS. This feedback appears in the form of a highlighted wireframe sphere around the SSRMS (Figure 3).

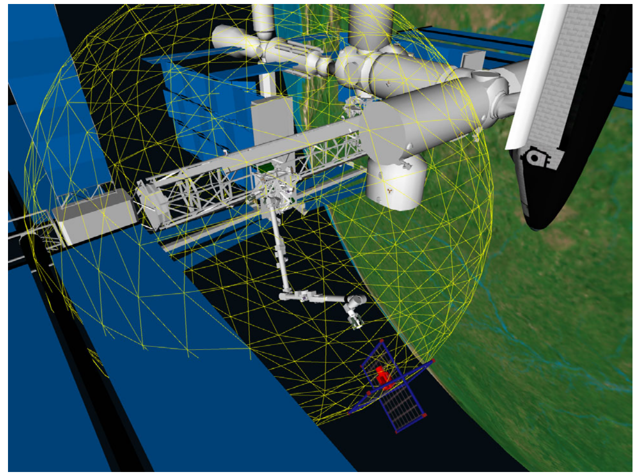

Fig 3. Illustration of the out-of-range visual feedback

4.2 Direct Grab Control

One of the most frequent tasks faced by SSRMS operators is to use it to grab a Grapple Fixture (GF) that acts as a payload handle or as an attachment for the SSRMS, which can walk on the ISS end-over-end, like a caterpillar, by grabbing itself from one GF to another.

GFs are located at different places around the ISS and on payloads. By having a virtual model of the ISS and its environment, the position of each GF is known in advance and thus leads to another control technique that is even simpler to use than the predictive pose control technique previously described.

This new control technique uses the power of VR and direct manipulation to highlight the different GF located on the ISS to help the operator locate them and select one directly, by clicking on it (Figure 4). This action allows the computer to determine the desired end pose for the end-effector since it is the pose necessary to grab the GF. A path planning algorithm completes the task by computing the necessary SSRMS control command to reach the desired end pose.

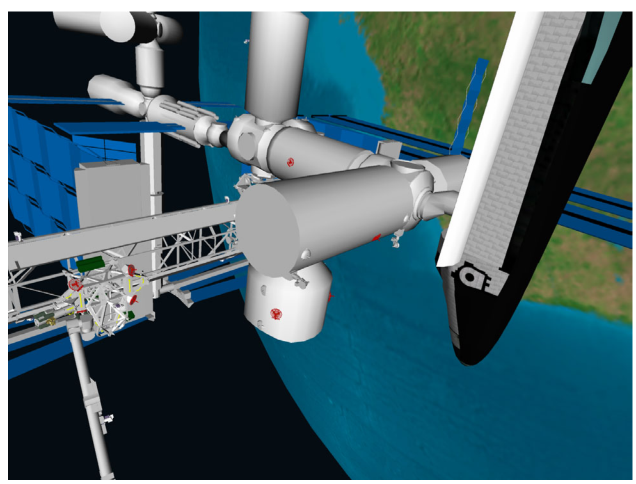

Fig. 4 Highlighted grapple fixtures on the ISS

Once again, if the desired pose is not reachable from the current pose of the arm, then a visual feedback (a highlighted wireframe sphere, as in Figure 3) appears momentarily around the SSRMS.

The direct grab control technique completely frees the operator from having to control the SSRMS and lets him supervise the operation instead, thus leading to significantly reduce cognitive workload.

4.3 Single Joint Rate Control

The single joint rate control discussed previously can also be called and controlled directly from COSMOS, by selecting a joint of the SSRMS. In this case, a bi-directional rotating arrow appears around the joint axis as illustrated in Figure 5. The operator can then directly control the joint, either by selecting one of the arrow signs or by using a hand controller, in order to reap the benefits of an accelerated predictive display.

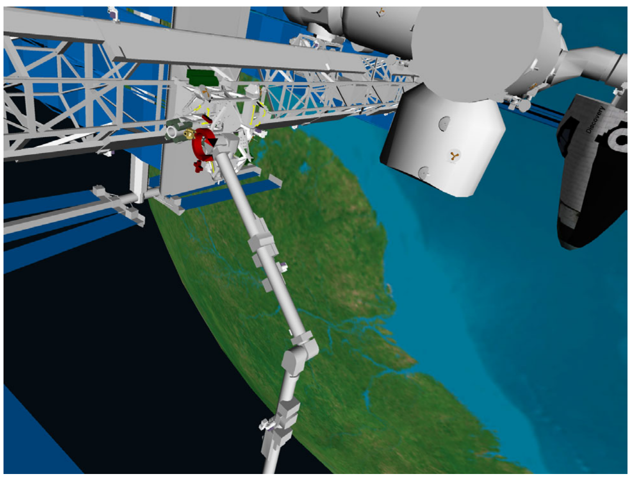

Figure 5. Single joint rate control of the SSRMS

5. Conclusion

The advantages of the presented proof-of-concept VR-based user interface for the control of the SSRMS are numerous.

First of all, the use of direct manipulation and accelerated predictive display, both for single joint and coordinated rate control, gives more time to focus operator attention on supervision of the operations, thus improving the safety of the operations. These new SSRMS control techniques alleviate the operator workload when compared to the current operator-in-the-loop control interface where the operator has to continuously control the robot arm from the initial to the final pose.

Also, the availability of a geometric model of the environment simplifies the task of grabbing a GF, since the operator simply has to highlight the GFs and select the desired GF.

Finally, the availability of multiple clear synthetic views of the environment can increase the situational awareness of the operator when compared to the current video feedback used.

The proposed new interface and control techniques have the potential to significantly reduce the learning time and improve the efficiency and safety of operation.

Also, the control interface described here could be useful both for space and ground operation of the SSRMS, since ground control is envisaged for future operations [21, 22, 7]. It could also be useful for use with the Shuttle Remote Manipulator System (SRMS) or other space robots, where the motion time from point to point is often considerable due to slow robot motion or communications delays.

The next step now is to validate this new proof-of-concept control interface by conducting a hands-on evaluation by real operators. Their feedback is essential to validate the concept and/or provide advice for further improvement before implementation.

For the implementation to take place, two other main elements are required to implement this new control interface on the real system.

The first element is a reasonably accurate and calibrated 3D graphical model of the environment (including the ISS, the SSRMS and all other payloads and objects located around them). An accuracy of the order of a few centimetres would probably be enough here, given a good calibration of the model with the environment [15, 18]. Fortunately, the creation of a faithful model of the environment, here the ISS, is now possible thanks to recent developments in spaceborne laser-based scanning systems [19].

Finally, in order to maintain and enhance the safety of the whole system, a proper path planning and collision avoidance module must be integrated. In the specific case here, where there is a moving robot in a static environment, we could use a system based on a real-time algorithm similar to the one described in [20]. If a potential collision is detected along the planned trajectory of the robot arm, the system could simply warn the operator which can then modify its strategy by using either a different control technique or by using the same one but in specifying intermediates end-effector poses along the trajectory to the desired final pose.

It is important to note that most of the advantages listed here are mainly applicable for free space non-contact tasks. For contact and close-to-contact tasks, the live video feed of the ISS and SSRMS cameras provide important visual information for the final contact phase. In that respect, the proof-of-concept interface presented here is not aiming at replacing the current interface but rather aims at augmenting it by providing an additional easy-to-use tool for SSRMS operators.

Finally, the new control techniques described here could also be applied to any ground-based systems where a robot is located in a static worksite, such as could be the case in a hazardous material waste depot.

6. Acknowledgements

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