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The future role of relay satellites for orbital telerobotics ☆

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Abstract

Orbital robotics focuses on a variety of applications, as e.g. inspection and repair activities, spacecraft construction or orbit corrections. On-Orbit Servicing (OOS) activities have to be closely monitored by operators on ground. A direct contact to the spacecraft in Low Earth Orbit (LEO) is limiting the operational time of the robotic application. Therefore, geostationary satellites are desirable to relay the OOS signals and extend the servicing time window. A geostationary satellite in the communication chain not only introduces additional boundary conditions to the mission but also increases the time delay in the system. The latter is not very critical if the servicer satellite is operating autonomously. However, if the servicer is operating in a supervised control regime with a human in the loop, the increased time delay will have an impact on the operator's task performance.

This paper describes the challenges, which have to be met when utilizing a relay satellite for orbital telerobotics. It shows a series of ground experiments that were undertaken with a relay satellite in the communication chain to simulate the end-to-end system. This case study proves that complex robotic applications in Low Earth Orbit (LEO) are controllable by human operators on ground.

Keywords: Orbital robotics; On-Orbit Servicing; Relay satellite; Human–machine interaction; Teleoperation

1. Introduction

This section gives a short overview on OOS applications and missions, which have demonstrated key software and hardware concepts for orbital robotics. Section 2 shows the increase of acquisition time due to the use of relay satellites, Section 3 outlines the challenges of relayed orbital robotics, whereas Section 4 describes the use of a data relay satellite in three case studies. Section 5 concludes the paper with test results, their importance, and future directions.

1.1. OOS applications

Similar to the benefits of terrestrial servicing and maintenance procedures, OOS is of great interest for spacecraft operators since it provides a wide spectrum of applications. OOS applications can be grouped into five main operations (Waltz, 1993), which are listed in Table 1 together with typical applications.

Assembly comprises the construction as well as the upgrade (e.g. with new instruments) of a spacecraft in orbit. It further comprises deployment operations as for example for solar panels. *Orbit transfer* operations involve not only orbit correction procedures, which are necessary

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Table 1
Overview of OOS operations with typical applications.

Operations	Typical application
Assembly	Spacecraft construction Spacecraft upgrade Deployment of appendages
Orbit transfer	Orbit corrections Retrieval from orbit Earth return
Maintenance and repair	Inspection Modification Cleaning and resurfacing Tests and checkout
Resupply	Consumables Components
Special	Emergency operations Scavenging Captive carrying

to reach a final target orbit, but also the retrieval from an orbit to a graveyard orbit. In addition, Earth return and controlled deorbiting are of further interest for, e.g. space debris removal missions. *Maintenance and repair* is historically one of the earliest objectives of an OOS mission. Here the typical applications of the servicer satellite reach from inspecting the target spacecraft (for e.g. deployment assurance, determination of the failure cause, health monitoring, etc.) to major modifications to the system, which include the actual repair. Test and validation of the refurbished elements can be necessary. Further, cleaning and surfacing may be needed for optical devices or enhancing thermal properties. Another option of OOS operations is to *resupply* the spacecraft with either consumables, that are depleted (e.g. propellants or coolants), or other components, which are necessary to maintain operations. This aspect has recently moved into the focus of research as, e.g. the Robotic Refueling Experiment shows (NASA, 2012). *Special* operations include emergency operations or scavenging applications, i.e. retrieving components from a (retired) spacecraft, which can be re-used for other missions, as planned in the DARPA Phoenix program ((DARPA, 2012). A further option, often considered for geostationary satellites, is the permanent use of the servicer for captive carrying. After docking with a depleted target satellite, the attitude and orbit control system of the servicer satellite will be responsible for controlling the attitude and station keeping maneuvers of the compound.

Thus, concepts of unmanned servicing missions were developed that are controlled from ground. Servicer spacecraft are foreseen to accomplish OOS operations at a target satellite. For that purpose the servicer satellite has to rendezvous and dock with the target satellite and execute complex operations. There is much research undertaken on spacecraft autonomy as will be seen in the next subsection, but there are only a few space missions considering a telepresent control of the spacecraft, which is of special interest for the work presented here. In telepresence control, the operator is provided with sufficient sensory information to allow her/him to accomplish the tasks as if (s)he were present at the remote site (Niemeyer et al., 2008). This concept is also referred to as functional presence. It requires a highly immersive operator interface providing high-fidelity visual and multi-modal sensor data, intuitive input devices, and a transparent communication link connecting the human operator to the robotic teleoperator (Hughes et al., 2003).

1.2. OOS missions in space

The first robotic manipulator in space, which was remote controlled from ground, was the Robot Technology Experiment (ROTEX) (Hirzinger et al., 2004). Aboard the space shuttle Columbia in 1993 it featured different various modes. Besides a tele-sensor-programming, an automatic, and a local on-board operation mode, the mission involved teleoperation of the spacecraft by a human operator from ground. The Japanese Engineering Test Satellite ETS VII (Oda, 2000) was in 1997 capable of demonstrating bilateral teleoperation in space. Inspection procedures and a series of manipulation operations, as well as autonomous capturing of a target satellite was demonstrated. Both ROTEX and ETS VII featured round trip delays in the vicinity of 6–7 s due to the use of the Tracking and Data Relay Satellite System[1] (TDRSS). The comparable high round trip delay, under which the human operator had to control the teleoperator was compensated by using predictive computer graphics. The human operator worked in virtual reality with a 3D model of the real environment. The human operator received instantaneous simulated (predicted) feedback to the actions, while they were executed in space a few seconds later and synchronized with the virtual reality afterwards. In contrast to these missions, featuring the possibility of human interaction, research is also performed on autonomous missions. An autonomous approach can be little fault-tolerant as the incidents in 2005 of the Demonstration of Autonomous Rendezvous Technology (DART) mission showed (Rumford, 2003). Launched to verify hardware and software for rendezvous and proximity operations, the main objectives included the demonstration of station keeping and collision avoidance maneuvres. However, when DART approached the target, it overshot an important way point and collided with it. A premature retirement of DART was the consequence. Nonetheless, successful autonomous OOS operations were demonstrated by XSS-10 (Davis, 2005) (2003, autonomous navigation and proximity operations), XSS-11 (AFRL, 2007) (2005, autonomous rendezvous and proximity operations), Orbital Express (Weismuller and Leinz, 2007) (2007, autonomous mission planning, rendezvous, proximity

[1] The majority of the time delay originated from the ground signal processing, switching, and possible encryption.