Acta Astronautica 102 (2014) 67–80

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Development and hardware-in-the-loop test of a guidance, navigation and control system for on-orbit servicing

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ARTICLE INFO

Article history:
Received 13 January 2014
Received in revised form
15 April 2014
Accepted 19 May 2014
Available online 29 May 2014

Keywords:
Orbital servicing
Ground-based rendezvous
Hardware-in-the-loop
Simulation
Navigation with delayed measurements
Telepresence

ABSTRACT

The rendezvous phase is one of the most important phases in future orbital servicing missions. To ensure a safe approach to a non-cooperative target satellite, a guidance, navigation and control system which uses measurements from optical sensors like cameras was designed and developed. During ground-based rendezvous, stability problems induced by delayed position measurements can be compensated by using a specially adapted navigation filter. Within the VIBANASS (VIsion BAsed NAvigation Sensor System) test campaign, hardware-in-the-loop tests on the terrestrial, robotic based facility EPOS 2.0 were performed to test and verify the developed guidance, navigation and control algorithms using real sensor measurements. We could demonstrate several safe rendezvous test cases in a closed loop mode integrating the VIBANASS camera system and the developed guidance, navigation and control system to a dynamic rendezvous simulation.

1. Introduction

Technology for on-orbit servicing is developed and missions demonstrating orbital servicing capabilities are currently in preparation [1–4]. Applications of on-orbit servicing are life time extension of partly damaged satellites and de-orbiting of in-operative satellites at the end of their life [5]. The rendezvous phase is one of the most critical parts of a robotic servicing mission since a safe approach to a non-cooperative target satellite must be conducted.

To approach a target satellite, optical sensors such as mono and stereo cameras can be used for relative navigation. Raw camera data is processed to provide a measurement of the relative position between the two spacecrafts. Alternatively, an operator on ground can be involved who marks the position of the target satellite in camera images and thus supports or replaces the automatic object recognition.

Rendezvous and docking via teleoperation can be done in the framework of a geostationary robotic serving mission like OLEV [3] and within a low Earth orbit mission using a data relay satellite [2]. A critical problem arising from the teleoperation concept is time delay. The delay can cause stability problems if the guidance, navigation and control (GNC) system is not specially developed to handle measurements with delay. Stability problems are very critical if high dynamics are involved. For example, during the ROKVISS experiment [6], where modern telerobotic technology was demonstrated, special control methods were applied to compensate for time delays. Using standard communication architecture, time delays of 2–5 s are expected for future geostationary on-orbit servicing [3] and even up to 10 s are expected in the ConeXPress-OLEV study [7]. About 7 s of delay (round-trip delay) was faced

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http://dx.doi.org/10.1016/j.actaastro.2014.05.023
0094-5765/

during the ETS-VII mission (Japanese Engineering Test Satellite VII) where a bilateral teleoperation experiment via a data relay satellite was performed [8].

Before an on-orbit servicing mission can be launched, intensive test, verification and validation of the rendezvous sensors and of the GNC system are necessary. Hardware-in-the-loop (HiL) simulations are suitable to test real hardware like cameras in an almost realistic scenario including simulation of illumination conditions and of the satellites' relative motion [9–11]. In a closed loop rendezvous simulation the full control loop can be tested consisting of sensor, processing unit, guidance, navigation, control and simulation of actuators and the spacecrafts' dynamical relative motion.

There are several approaches for rendezvous to a non-cooperative satellite in space. In [12], the authors cope with the problem of recognizing an uncooperative target satellite. Pose estimation methods for rendezvous and docking applications are proposed in [13]. A GNC system for rendezvous is presented in [14]. First demonstrations of ground-based rendezvous were already performed in the extended phase of the PRISMA mission. The German Aerospace Center demonstrated a controlled approach from 30 km to 3 km in the ARGON (Advanced Rendezvous demonstration using GPS and Optical Navigation) experiment [15].

Different ground facilities exist for testing GNC algorithms and simulating rendezvous and docking maneuvers. In the framework of an Italian project called STEPS (Systems and Technologies for Space Exploration) a Rendezvous and Docking simulator based on an air-floating test bed (2D platform) and GNC algorithms are developed [16]. Hardware-in-the-loop tests of a 3D LIDAR (Light Detection and Ranging) executed at the Spacecraft Robotics Engineering and Controls Lab of the U.S. Naval Research Laboratory are described in [17]. The authors observed also time delays induced by the sensor hardware and by data interfaces. The European Proximity Operations Simulator (EPOS) 2.0 [18,9] is a robotic based test bed allowing for rendezvous and docking simulation and sensor and GNC system verification. Several hardware-in-the-loop tests without simulating time delay have been conducted [11]. EPOS 2.0 was also involved as test facility in the VIBANASS project (VIsion BAsed NAvigation Sensor System). In this project an optical rendezvous and docking camera system was developed [19] and tests and verification of the camera system were conducted at the simulator EPOS 2.0 in an open loop mode for verification of the sensor system and the image processing module [20,21]. An overview of ground verification methods and facilities is given in the survey article [22].

Development of a GNC system which can handle delayed measurements and test of the entire control loop during an approach under realistic conditions are still open research tasks. In particular, a safe approach has to be tested and demonstrated using real sensor data within a hardware-in-the loop simulation. The stability of the control loop in the case of delayed measurements has to be proved. In the final VIBANASS test campaign, a secondary goal was to demonstrate closed loop rendezvous simulation with the VIBANASS camera system. Existing approaches [11] using Kalman filter techniques had to be consequently modified for this task.

The objective of this paper is to present a hardware-in-the-loop simulation for testing closed loop rendezvous processes within the VIBANASS test campaign at EPOS. The main task is to develop a guidance, navigation and control system resulting in a stable control loop even in the case of delayed position measurements.

Throughout the paper, a *closed loop simulation* is a simulation in which the output of a GNC system is fed back to the simulation of the actuators and spacecrafts' dynamics. Thus, the trajectory of an approach is not predefined but computed in real-time. The trajectory depends on the sensor measurements, the guidance values and the design of the navigation filter and of the controller. *Time delay* is the time difference between the capturing of the images by a camera and the time when the measurements are available for the navigation system. The active satellite in an on-orbit servicing mission is called *servicer* or *chaser*; the passive satellite is called *client* or *target*.

2. Methods

2.1. Hardware-in-the-loop simulator EPOS 2.0

EPOS, the European Proximity Operations Simulator, is a hardware-in-the-loop simulator focusing on the last phase (25–0 m) of Rendezvous and Docking (RvD) maneuvers involving two spacecraft. The simulation concept of EPOS takes advantage of both physical and computer simulation: on one hand, satellite dynamics cannot be simulated physically on ground for any practical purposes, while numerical simulation can be realized easily and leads to very good results. On the other hand, realistic sensor output including various physical effects is very difficult to simulate with sufficient quality by pure numeric software. EPOS allows for the combination of numerical satellite dynamics simulation and real RvD sensor hardware.

Fig. 1 illustrates the facility layout. The central elements constitute two standard industrial robots. Robot 1 in Fig. 1 is a KUKA KR100HA, which can carry a maximum payload of 100 kg. It is mounted on a linear rail with a length of 25 m. The robot can be moved on that rail in order to simulate the relative distance of two satellites in space. The other robot (robot 2) is a KUKA KR240. Its maximum payload is 240 kg. In contrast to robot 1, it is mounted at the end of the rail, its base fixed in the laboratory. Each robot is equipped with a breadboard attached to the tool flange which can be used to mount satellite mockups or sensor devices.

If visual RvD sensors are involved, realistic reproduction of light with a Sun-like irradiation intensity and a spectrum is crucial. For example, during VIBANASS open-loop tests (cf. Section 2.2) realistic illumination conditions including different incident angles had to be realized. For that purpose, a spotlight with a spectrum very close to the Sun is used at EPOS [10].

2.2. VIBANASS test campaign on EPOS

In the VIBANASS project an optical rendezvous and docking camera system was developed [19,21,23]. The