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Laboratory experiments of resident space object capture by a spacecraft–manipulator system

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ABSTRACT

A set of laboratory experiments are conducted to demonstrate the autonomous capture of a simulated resident space object by a simulated spacecraft equipped with a robotic manipulator. A planar air-bearing test bed provides a quasi-weightless and drag-free dynamic environment on a plane. To control the chaser's base, floating, flying, and rotation-flying control approaches are implemented and compared. A resolved-motion-rate controller is used to control the manipulator's joints. Using these control methods a floating object at rest is successfully captured. Furthermore, the capture of a floating and rotating object is demonstrated using a flying base control approach. The originality of these experiments comes from the remarkably high dynamic coupling of the spacecraft–manipulator system used. Emphasis is given to the guidance and control problems, with the relative navigation problem being left outside the scope of this effort.

1. Introduction

Many future space missions (*e.g.*, servicing, inspection or active debris removal) may require the use of robotic manipulators to capture cooperative or non-cooperative Resident Space Objects (RSO). The dynamics of space-based manipulators substantially differ from their terrestrial counterparts, as the base-spacecraft, not being anchored to the ground, is free to react to the manipulator's motion. The effects of this dynamic coupling intensify as the base-spacecraft to manipulator mass and inertia ratios decrease. Adding onto the inherently nonlinear manipulator dynamics, systems that exhibit a large dynamic coupling present a particularly challenging modeling and control problem. Other hardware related non-linearities (*e.g.*, contact dynamics, friction, structural flexibility, joint backlash or signal time delays) further magnify the challenge.

Extensive analytic work and numerical simulations have been devoted to the modeling and control of spacecraft–manipulator systems, chiefly focusing on RSO capture [1–3]. The scarcity of suitable test facilities to recreate the complex dynamic phenomena [4,5] has made the equivalent experimental-based work exceedingly rare [6–15].

The growing interest and adoption of small spacecraft has stimulated multiple mission designs that feature robotic manipulators mounted on small spacecraft, which result in highly coupled systems [16–19]. The dynamic complexity of these space-robotic systems, difficult to recreate in a numerical simulation environment, justifies the use of high fidelity experimental facilities to validate, verify and demonstrate the feasibility of robotic spacecraft maneuvering for this class of highly coupled systems [20].

In this paper, the autonomous capture of an RSO by a spacecraft–manipulator system with a large dynamic coupling is demonstrated in a laboratory environment. Floating, flying, and rotation-flying base-spacecraft control approaches have been experimentally demonstrated and compared. This demonstration exclusively focuses on the guidance and control problems and has been carried out in a test facility that replicates the drag-free and weightless conditions of spaceflight. The dynamic fidelity of the test bed, combined with the hardware related effects of the test vehicles, provide a level of realism remarkably difficult to recreate in a numerical simulation setup.

The POSEIDYN[1] air-bearing test bed [21] is used here to provide a quasi-frictionless and weightless dynamic environment on a plane. To achieve these dynamic properties, the test vehicles float, via planar air bearings, over a horizontally leveled 4-by-4 meter granite table. The chaser's spacecraft–manipulator system is composed of a Floating Spacecraft Simulator (FSS), acting as the base-spacecraft, and a four-link kinematically redundant robotic manipulator. To generate the requested forces and torques the chaser base-spacecraft is equipped with eight cold-gas thrusters and a

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[1] POSEIDYN is a backronym standing for Proximity Operation of Spacecraft: Experimental hardware-In-the-loop DYNamic simulator.

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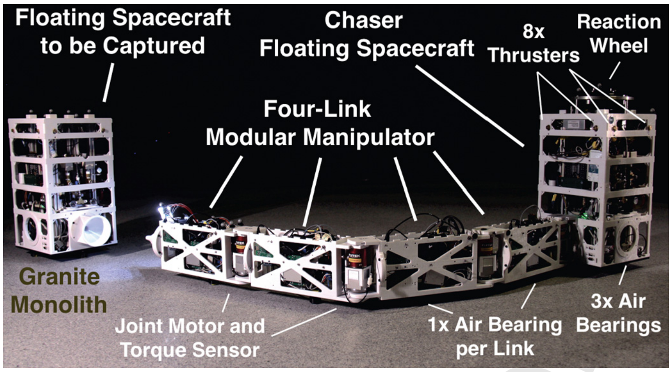

Fig. 1. Target and chaser FSS with robotic manipulator in the POSEIDYN test bed at the Spacecraft Robotics Laboratory.

reaction wheel. A second FSS is used to simulate the RSO to be captured and an overhead motion capture system is used to determine the position and orientation of the test vehicles. See Fig. 1 for an overview of the experimental setup. The experiments presented here are a continuation of an earlier set of experiments conducted by the authors in the POSEIDYN test bed [22].

Previously flown and experimentally tested spacecraft–manipulator systems have exhibited substantially more benign mass and inertia ratios than the ones found in the spacecraft–manipulator system used for this set of experiments. The Space Shuttle orbiters with their Shuttle Remote Manipulator System [23], the International Space Station (ISS) with its Space Station Remote Manipulator System [24], the ETS-VII [25], and the Orbital Express [26,27] exhibited mass ratios ranging from ∼222 for the ISS down to ∼15 for the Orbital Express mission.

Laboratory-based hardware-in-the-loop systems have gone down to mass ratios of 2.2. Of particular importance are the experiments of Umetani and Yoshida, who demonstrated the capture of static and moving objects using a spacecraft–manipulator system with a single two-link manipulator with a mass ratio of 4.5 [7,11]. More recently, the Space Research Centre of the Polish Academy of Sciences experimentally demonstrated the controllability of two-link system with a mass ratio of 2.15 [20].

The distinctive aspect of these experiments presented here is the relatively small base-spacecraft used (in terms of mass and inertia). With a base-spacecraft to manipulator mass ratio of ≈ 1 and an inertia ratio of $\approx 1/50$ (with a fully extended manipulator), the dynamic coupling of the system is remarkably prominent. Furthermore, the four-link kinematically redundant manipulator also represents an increase on the dynamic complexity with respect to past laboratory-based experiments. In summary, the experiments presented here advance the experimentally demonstrated state-of-the-art of robotic spacecraft maneuvering.

The rest of this paper is organized as follows. The considered capture scenarios are presented in Section 2. Then, the proposed guidance and control laws are presented and discussed in Section 3. A detailed overview of the experimental setup is provided in Section 4. Finally, in Section 5 the experimental and numerical simulation results are presented, and in Section 6, these are analyzed and discussed.

2. Test scenario

For the experimental demonstration two distinct scenarios have been considered. The first involves a floating RSO at rest, while the second considers a floating and rotating RSO.

The RSO at rest case represents a scenario where the target RSO maintains a constant and fixed attitude and position. This is experimentally achieved by having the target FSS floating over the granite monolith while using its onboard thrusters to keep its position and orientation. In the rotating RSO scenario, the target RSO orientation changes at a constant rate. In this instance, the target FSS also controls its position, orientation, and angular rate using its onboard thrusters. As both the chaser and target FSS are floating on the granite table, the contact dynamics experienced during the capture maneuver will have a disturbing effect on their positions and orientations.

The final close-in approach to the RSO and its subsequent capture are the only maneuver phases considered and experimentally evaluated in this study (*i.e.*, far range rendezvous is ignored). During these final phases, the double integrator dynamics provided by the POSEIDYN test bed are an acceptable approximation to the real relative dynamics between two orbiting vehicles. In fact, when the chaser and the target RSO remain in close proximity and the maneuver duration is small when compared to the orbital period, the effects of the relative orbital dynamics can be treated as negligible perturbations.

3. Design and analysis of the guidance and control laws

To achieve the capture of the target FSS, a four-phased maneuver is adopted. Fig. 2 notionally shows these phases.

*Ph.*1 *Initial approach phase* (fly to initial hold position). The chaser closes in on the target FSS, adopting a hold position in its proximity. During this initial maneuver the manipulator is in a folded configuration, minimizing the vehicle's overall inertia and enhancing its maneuverability.

*Ph.*2 *Manipulator unfolding phase*. The chaser's manipulator is unfolded, adopting its pre-capture configuration. During the unfolding maneuver, the base-spacecraft is not controlled, leaving the base-spacecraft to freely react to the manipulator's motion and saving control effort. This base reaction is pre-computed and accounted for when selecting the initial hold position (at the end of *Ph.*1). The goal is to have the chaser directly facing the target after the unfold maneuver is completed.

*Ph.*3 *Final approach phase* (fly to pre-capture hold position). The chaser moves to the pre-capture hold position, refining its alignment and bringing the target FSS within a pre-determined capture range.

*Ph.*4 *Capture phase*. The chaser captures the target FSS by extending its robotic manipulator and using the base-spacecraft actuators. Ideally, the pre-capture hold position at the end of *Ph.*3, allows the manipulator's to capture the target FSS by moving its end-effector in a straight line.

Note that in Fig. 2, as well as in subsequent figures, the black cross indicates the location of the chaser's Center-of-Mass (CoM) and the dashed line indicates its trajectory.

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