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HARDWARE-IN-THE-LOOP PROXIMITY OPERATIONS IN CISLUNAR SPACE

Abstract

NASA's Gateway mission is being developed as a long-term hub, potentially including humans on-board and offers logistical support for various future missions. Consequently, cargo delivery and refueling modules will require precise rendezvous and docking techniques for longevity of the Gateway facility.

A rendezvous technique in the cislunar space is proposed in this investigation, one that leverages coupled orbit and attitude dynamics in the Circular Restricted Three-body Problem (CR3BP). An autonomous Guidance, Navigation and Control (GNC) technique is demonstrated in which a chaser spacecraft approaches a target spacecraft in the southern 9:2 synodic-resonant L2 Near Rectilinear Halo Orbit (NRHO), one that currently serves as the baseline for the Gateway. Hardware-in-the-loop laboratory experiments are conducted to validate the guidance algorithm, with observations supplemented by vision-based navigation techniques. Optical sensors on-board chaser spacecraft determines the pose of the target spacecraft during the approach phase.

Relative equations of motion for the chaser spacecraft relative to the target along the NRHO are derived in the CR3BP. Attitude dynamics for the target and chaser spacecraft are determined, influenced by gravity-gradient torques exerted by the Earth and the Moon. A nonlinear control algorithm using Interior-Point Optimization (IPOPT) technique is incorporated to identify an optimal rendezvous path, both orbital and attitude.

The proposed guidance and control algorithm are tested via hardware-in-the-loop experiments in the ZeroG-Lab facility at the University of Luxembourg. Scaled mockups of CubeSats are mounted on the end-effectors of two robotic manipulators and the trajectory and attitude motion in the cislunar environment are simulated. Further, optical sensors mounted on the chaser spacecraft, in form of a monocular camera, detect semantic features on the target spacecraft. Using the correspondence of the detected keypoints in the known wireframe model of the target, an Efficient Perspective-n-Point (EPnP) solver estimates the relative pose of the target. A Kalman filter processes these pose observations and deliver precise state estimates, and run alongside the control algorithm. Any deviations from the predetermined path are

overcome by a linear controller. The efficacy of the GNC technique is tested by considering a complex scenario in which the rendezvous operation is conducted with a non-cooperative tumbling target.

The advancements in GNC algorithm to actively support rendezvous operation, with onboard vision-based navigation equipment enables exploitation of such operations in shadow regions, for example, away from the line of sight from the Earth. Such techniques further augments capability to conduct rendezvous in deep space, significantly farther from Earth.