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HARDWARE-IN-THE-LOOP VALIDATION OF GNC ALGORITHMS FOR AUTONOMOUS NANOSATELLITE SWARMING MISSIONS TO ASTEROIDS

Abstract

The Autonomous Nanosatellite Swarming (ANS) project is a collaborative effort by Stanford's Space Rendezvous Laboratory (SLAB) and NASA Ames Research Center to advance the Guidance, Navigation, and Control (GNC) technologies required for small body exploration using a formation of small, autonomous spacecraft. ANS fuses advanced feature-tracking and filtering algorithms to achieve simultaneous navigation and estimation of the gravity field, rotational motion, and shape of the body from optical imagery and intersatellite radio-frequency measurements. It also leverages innovative methods for optimal guidance and maneuver-planning to maximize scientific output while ensuring formation safety. Due to the prohibitive cost of flying a technology demonstration mission to a small celestial body, rigorous ground testing and validation of algorithms are essential to advance the state of the art and enable future missions. The major contributions of this paper are an overview of the multi-tiered, hardware-in-the-loop testing methodology used to validate GNC algorithms for the ANS project, and the presentation of results and lessons learned. This campaign is the first to unite three platforms developed in SLAB for testing vision-based GNC systems. The core component is a suite of software tools for high-fidelity satellite orbit and attitude propagation as well as synthetic image generation. Second is a variable-magnification optical stimulator, which utilizes the aforementioned toolset to render scenes consisting of stellar and non-stellar objects for capture on a real satellite sensor. Last is a testbed featuring two robotic arms, one with six and one with seven degrees of freedom, and photometrically calibrated devices to emulate the illumination conditions in space. Using one arm to orient a 3D-printed asteroid and the other to simulate satellite motion with a camera, the testbed is able to produce realistic space imagery without synthetic rendering. The ANS algorithm validation campaign is centered around three open- and closed-loop scenarios with the asteroid Eros serving as the central body. The detailed imagery, geometry, and gravity model of Eros produced by the NEAR Shoemaker mission provide a baseline for calibration of the testbed as well as algorithm evaluation with a real reference body. The selected scenarios increase in complexity, assessing and stressing both the GNC algorithms and testing environments. Each scenario is run first in software with purely synthetic imagery and motion propagation, then using the optical stimulator to obtain images of a rendered scene on a real sensor, and finally using the robotic testbed to obtain sensor images of a physical scene.