Autonomous Asteroid Characterization through Nanosatellite Swarming

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I. EXTENDED ABSTRACT

Asteroids are of great interest due to scientific value, resource potential, and asteroid-Earth collision prevention. Asteroid missions to date depend extensively on human oversight and Earth-based resources such as NASA’s Deep Space Network. They also rely on power- or computation-intensive shape recovery methods like laser altimetry or stereo-photoclinometry. This paper addresses the distributed navigation and asteroid characterization of the mission concept called Autonomous Nanosatellite Swarming (ANS). ANS reduces mission cost, duration, and use of oversubscribed ground-based resources, enabling a greater number of future small body missions.

ANS consists of multiple autonomous nanosatellites cooperating to characterize an asteroid. Each spacecraft is equipped with minimal low size, weight, power, and cost avionics: a two-way radio-frequency (RF) antenna, a short-range camera, and a star tracker. Upon initial approach, a brief ground-in-the-loop phase uses optical navigation and ground-based RF measurements to initialize the spacecraft states and a sparse database of asteroid surface landmarks using keypoint descriptors. This paper assumes this phase is complete. After initialization, the spacecraft autonomously track landmarks, update the landmark database, and simultaneously estimate the spacecraft states and asteroid properties. This process is divided into two subsystems.

The first subsystem optically detects and tracks landmarks and initializes their 3D position estimates. Landmarks are detected in images using keypoint detection. Database points are correlated to landmarks in the images via Mahalanobis distance, leveraging the output of the estimation filter. Newly identified landmarks are projected into 3D space using multi-agent structure from motion and added to the database. While these computer vision techniques are common for Earth applications, they have not been used together in a distributed, multi-satellite mission like ANS. These techniques require less processing and memory, and they are better suited for distributed systems than traditional natural feature tracking and shape recovery methods.

The second subsystem fuses the pixel measurements of tracked landmarks with inter-spacecraft RF measurements in an unscented Kalman filter (UKF) to simultaneously estimate the spacecraft states, landmark 3D positions, asteroid gravity spherical harmonic coefficients, and asteroid rotational parameters. The UKF runtime is reduced with no loss of accuracy and is made robust to dynamics modeling deficiencies through the recently developed exploiting triangular structure and adaptive state noise compensation techniques. A global asteroid shape model is obtained through a least squares fit of the coefficients of a spherical harmonic shape model to the estimated landmark positions. A novel regularization procedure provides surface smoothness between landmark estimates.

The ANS architecture is validated through simulation of a three-spacecraft swarm orbiting asteroid 433 Eros with a physical spacecraft camera in the loop, stimulated by an optical stimulator. The required accuracy of the initialization phase for successful autonomous operations is quantified, and two different keypoint descriptors, SIFT and SURF, are utilized to verify which is better suited to ANS. The resulting asteroid characterization accuracy is compared to that of the Near-Shoemaker mission to Eros to illustrate the advantages of ANS over a traditional mission architecture.