TOWARDS AUTONOMOUS OPTICAL NAVIGATION: APPROACH AND PROXIMITY OPERATIONS STRATEGY FOR THE EMIRATES MISSION TO THE ASTEROID BELT

Jacopo Villa[16*], Mattia Pugliatti[27], Mohamed Salem[36], Reem Klaib[36], Jay McMahon[47] and Jeremy Knittel[56]
[1]EMA Optical Navigation Lead, [2]Postdoctoral Associate, [3]Flight Dynamics Engineer, [4]Associate Professor, [5]EMA Flight Dynamics Lead [6]Laboratory for Atmospheric and Space Physics, 1234 Innovation Dr, Boulder, CO 80303
[7]University of Colorado Boulder, 3775 Discovery Dr, Boulder, CO 80303 [*][jacopo.villa@lasp.colorado.edu]

Abstract. *We introduce the optical-navigation strategy developed for approach and proximity operations at asteroid 269 Justitia, which is planned to be visited by the Emirates Mission to the Asteroid Belt in 2034. Unlike traditional landmark-based navigation, requiring the manual selection, tracking, and updating of a surface-landmark catalog, the proposed approach leverages the asteroid silhouettes and surface point clouds as optical-navigation measurements. The proposed strategy employs a "waterfall" pipeline, wherein the output of each algorithm serves as the input for the subsequent algorithm, as more knowledge of the target becomes available. This landmark-free paradigm simplifies and automates the overall navigation-and-characterization process, while proving robust to changes in lighting conditions and viewing geometry which will be encountered.*

Introduction. The Emirates Mission to the Asteroid Belt (EMA), led by the United Arab Emirates and developed in collaboration with the University of Colorado Boulder's Laboratory for Atmospheric and Space Physics, will send the MBR Explorer spacecraft to visit seven targets in the asteroid belt. The spacecraft is planned to fly by six main-belt, unexplored asteroids and rendezvous with a 7th asteroid. The mission's science goal is to improve understanding of water- and carbon-rich asteroids in the Main Belt. The rendezvous target is 269 Justitia: a particularly interesting asteroid due to its very red spectrum, perhaps indicating an origin in the outer solar system. The mission plan includes performing a series of mapping campaigns and delivering a lander to the asteroid surface. In this work, we present the optical-navigation (OpNav) strategy which will be used during approach and proximity operations at Justitia.

Optical Navigation at Small Bodies. OpNav in the vicinity of small celestial bodies relies on extracting target-relative measurements from surface imagery to estimate the spacecraft orbital motion and characterize the small-body properties, e.g., its gravity field, rotational motion, and shape. In many cases, this process poses unique challenges: due to the irregular shape and topography of small bodies, the surface appearance changes continuously due to the evolving lighting conditions and camera-viewpoint geometry.

State of the Practice. In prior missions, this problem has been tackled using landmark-based navigation techniques, most notably, Stereophotoclinometry (SPC).[1] In such a case, a catalog of surface landmarks—distinctive features that are identifiable in imagery from multiple camera views—is selected and progressively updated by ground-based operators. Then, the appearance of the surface surrounding landmark points is predicted, using a-priori shape-and-albedo models, and then registered with the landmark observed in imagery. Through the registration process, a camera-to-landmark line-of-sight measurement is extracted and the surface model can be updated. To effectively perform this technique, both a high-resolution surface model and a landmark catalog need to be built and updated. Further, it is often necessary to observe the surface under different lighting conditions in order to disambiguate local-slope and albedo estimates. This process requires extensive target-characterization phases and complex ground operations.

Proposed Approach. To reduce operational timelines and complexity, we propose a novel, landmark-free paradigm for OpNav and characterization at small bodies. Instead of relying on a catalog of predefined surface landmarks and a high-resolution surface model, we leverage *global* features extracted from small-body imagery: the body's silhouette—the contour separating the irregular object from the dark background—and a point-cloud representation of its surface. These measurement types are used for pole estimation, shape reconstruction, and terrain-relative navigation purposes. Further, they prove robust to changes in lighting conditions and viewing geometry, greatly simplifying and automating the OpNav process. Lastly, the usage of silhouette and point-cloud measurements is based on simple geometric principles, which simplifies the derivation of measurement uncertainties and hence the integration within an orbit-determination (OD) filter. The presented strategy relies on two assumptions: the camera is calibrated and a sufficiently accurate camera-attitude estimate is available; we will discuss the sensitivity to these assumptions.

Overview of Algorithmic Pipeline. The proposed OpNav strategy for approach and proximity operations is based on a "waterfall" pipeline, as shown in Figure 1, where target-characterization and navigation tasks are performed sequentially. The rationale for the waterfall strategy is twofold: (1) different physical quantities of interest become observable at different times throughout the mission and (2) some quantities require prior knowledge to be estimated, whereas the reverse dependency does not hold. As such, the waterfall approach allows to progressively build knowledge as more quantities are estimated. The algorithms are executed throughout three consecutive mission phases: approach, Initial Mapping Orbit (IMO), and Primary Science Orbit (PSO). An overview of each OpNav algorithm is provided in the following. Traditional centerfinding algorithms will also be employed but are not discussed here.

Pole Estimation. The asteroid pole (rotation axis) can be extracted from low-resolution imagery, typically during the approach phase, and hence is the first estimated parameter. Once the irregular silhouette of the small body becomes clearly visible in imagery—usually when the object spans tens to hundreds of pixels across the image—its axis of rotation can be estimated. We use the Principal Axis of Rotation from Silhouette (PARS) algorithm, which leverages symmetries in the silhouette evolution relative to the pole projection onto the image. The key principle is extracting the symmetry of the silhouette evolution about the pole direction. Consider a set of consecutive images such that the pole projection onto the camera plane is considered constant. Then, the image obtained by co-adding multiple silhouette observations acquired as the asteroid rotates exhibits some level of reflective symmetry with respect to the pole projection. This effect is due to each surface point following an elliptical arc about the pole direction, as seen in the image plane. By extracting the direction of maximum symmetry in the co-added silhouette image, a projected-pole direction is estimated. To improve robustness to error sources such as shadowing and image-alignment, the Discrete Fourier Transform is employed and symmetry detection is performed in the frequency domain. By repeating the process from multiple pole perspectives—in our case, leveraging latitudinal changes occurring through the approach trajectory—pole-projection measurements are triangulated and the 3D pole direction is estimated.

Visual-Hull Reconstruction. Based on the pole and rotation-period estimates previously obtained, an asteroid-fixed frame is defined. Then, silhouette images from multiple camera views are registered with each other in the asteroid-fixed frame to bound the shape of the observed asteroid. This process is known as Shape-from-Silhouette (SfS), an established technique in computer graphics previously applied to asteroid-mission scenarios.[2] The key principle behind SfS is that each silhouette, and the associated camera viewpoint—assumed to be known—bound the occupancy of the imaged volume from that viewpoint. By combining such spatial constraints from multiple silhouettes, a so-called *visual hull* is obtained: the 3D volume which describes all the silhouette observations. The fundamental limitation of the visual hull is that local concavities, such as craters, cannot be observed. The SfS procedure is also started during approach, when the object spans hundreds of pixels across the image, and continues throughout IMO to improve the shape resolution and cover previously-unobservable surface regions.

Limb-based Navigation. Once the visual-hull shape model is available, it is used for limb-based terrain-relative navigation, using an algorithm called LimbNav. The proposed technique consists in (1) predicting the appearance of the light-robust limb of the object—i.e., the silhouette portion facing directly toward the sun direction in the camera plane—using the a-priori shape model and OD solution, (2) extracting the light-robust limb from the observed image, (3) registering the predicted and observed limbs using an Iterative Closest Point (ICP) algorithm, (4) computing a camera-position update based on measurement residuals, and (5) repeating the process until convergence. This process returns an up-to-scale position measurement in the asteroid-fixed frame. LimbNav is the primary navigation algorithm during IMO.

Point Cloud-based Navigation and Mapping. During PSO, the surface becomes sufficiently resolved to use a point cloud-based approach. Specifically, we use a navigation and mapping algorithm named CloudNav. As discussed, identifying and tracking the same surface landmarks across multiple images and viewing conditions proves challenging for small-body surfaces. Instead, CloudNav relies on only tracking visual features between consecutive, highly-overlapping images to avoid exceedingly large lighting and viewpoint changes. Then, such tracks are used to extract a surface 3D point cloud. The algorithmic steps consist of: (1) tracking visual features between consecutive images, (2) extracting a camera direction-of-motion measurement from such feature tracks, (3) triangulating the feature tracks to extract a sparse point cloud of the surface, using feature tracks and a-priori knowledge on the camera pose, (4) estimating the camera pose by registering the extracted point cloud with a reference point cloud, using a variant of the ICP algorithm. We use two modes for the CloudNav algorithm: the mapping-and-odometry (CloudNav-M) mode, used for high-resolution shape reconstruction, where consecutive point clouds are registered with each other to progressively build a map of the asteroid; and localization mode (CloudNav-L) where each point cloud is registered with the previously-reconstructed shape model. CloudNav-L returns an up-to-scale camera-pose measurement and the associated uncertainty, based on an analytical covariance model, which is fed to the OD filter.

Acknowledgements. Funding of the Emirates Mission to Explore the Asteroid Belt is provided by the United Arab Emirates Space Agency.

References.

[1] R. Gaskell, O. Barnouin-Jha, D. J. Scheeres, A. Konopliv, T. Mukai, S. Abe, J. Saito, M. Ishiguro, T. Kubota, T. Hashimoto, *et al.*, "Characterizing and navigating small bodies with imaging data," *Meteoritics & Planetary Science*, vol. 43, no. 6, pp. 1049–1061, 2008.

[2] I. A. Nesnas, B. J. Hockman, S. Bandopadhyay, B. J. Morrell, D. P. Lubey, J. Villa, D. S. Bayard, A. Osmundson, B. Jarvis, M. Bersani, *et al.*, "Autonomous exploration of small bodies toward greater autonomy for deep space missions," *Frontiers in Robotics and AI*, vol. 8, p. 650885, 2021.

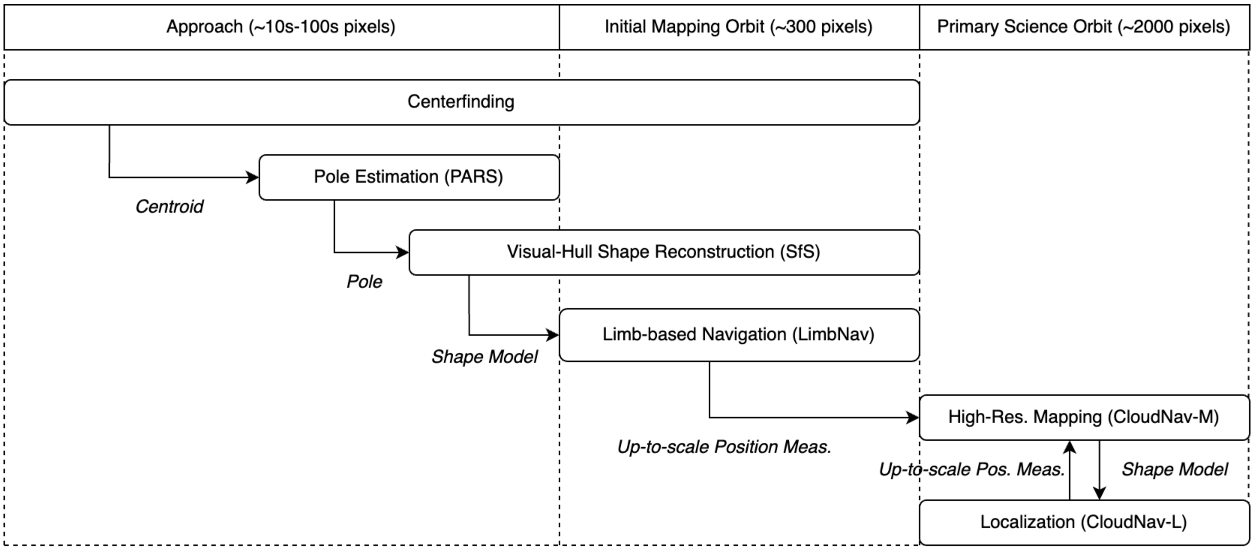

Figure 1. Diagram illustrating the "waterfall" pipeline adopted for approach and proximity operations at asteroid Justitia during the EMA mission. Top square blocks represent mission phases, with approximate asteroid-span estimates reported in parentheses. Each rounded block represents an algorithm, whose name is reported in parentheses. Arrows represent algorithms output data, described by their labels in italic. Credit: EMA