

# CAMERA-AIDED INERTIAL NAVIGATION FOR PINPOINT PLANETARY LANDING ON RUGGED TERRAINS

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This paper tackles the pinpoint navigation challenge for autonomous planetary landers using a single camera and an Inertial Measurement Unit (IMU) to reach a 100-meter position error requirement at touchdown. Inertial navigation schemes embedded in previous missions suffer from position and attitude (pose) error growth due to integration of IMU acceleration and angular rate measurement errors. When looking down at a terrain in sunlight conditions, image data provided by the camera allow for identifying surface features from reference maps. These absolute landmarks prevent the error growth. At the same time, image features are tracked at a higher rate through the image sequence to make the absolute landmark matching step more robust. Feature tracking will eventually limit error drift at low altitude when the map resolution is too poor to be useful. IMU data allow high-bandwidth, low-delay state estimation in any environment condition and is capable of solving the scale problem associated to camera measurements. Inertial and optical data fusion is implemented through extended Kalman filtering which tightly integrates image feature points measurements to IMU-based state propagation. Tight integration of visual and inertial measurements within the navigation filter allows for working in degraded conditions with a few features only and thus is more robust than vision-only solutions. Image measurements provided by a camera are bidimensional by definition. Many times in literature, a planar terrain is assumed to avoid computationally-costful methods dealing with highly-3D areas. Though, such terrains will be encountered in future planetary exploration missions, for instance to the mountainous lunar south pole. Two aspects that are the most challenging over rugged terrains are matching absolute landmarks with the on-board map and estimating depth of relative features to predict their images coordinates in the correcting part of the filter.

The first contribution of this work is the definition of an absolute landmark matching process that uses landmark constellations, designed as an extension of Landstel [1], to work over any type of terrain, from flat to hilly. Another contribution is its integration within a full-state navigation filter able to cope with computer requirements associated with space exploration missions.

We compute a landmark constellation at each point of interest selected in an orbital image from an image intensity criterion. 3D coordinates of the point and its neighbors are extracted from a digital elevation model in order to account for terrain relief. The constellation itself is based on the angular and distance distributions of its neighbors, stored in a signature vector. Not only are the constellation signatures robust to terrain topography and illumination changes, but they can adapt to all surface features while maintaining low-memory requirements.

Once a landmark is matched with the map, its true 3D coordinates are used to build an absolute image measurement in the filter. Relative image measurements coming from other features are relying on the estimation of the 3D position of image features to predict their image coordinates and subsequently update the filter. We compare the performance for two state-of-the-art tight fusion schemes: Simultaneous Localization And Mapping filters (SLAM), and Sliding-Windows filters (SW). The SLAM approach estimates the spacecraft pose parameters along with 3D positions of the image feature points in the state vector of the filter. Visual measurements can be processed without delay but SLAM has a high computational cost associated to a large state vector. For many descent trajectories, points are only crossing the camera field of view for a limited period of time. We thus process SLAM feature points in a limited temporal window from the last image backwards and discard them when they leave the field of view to decrease the computational cost. The other approach is a SW filter [2]. Unlike SLAM, it only estimates spacecraft pose parameters, but keeps previous camera poses in the state vector for a limited and sliding temporal window in order to process measurements. These measurements are built by triangulating 3D positions of a point from the first and last image of the sequence where it appears. Measurements are thus delayed and 3D reconstruction of points is less accurate than SLAM, but the computational cost is lower.

SLAM-based and SW-based version of our navigation system were implemented in an orbit-to-touchdown lunar descent and landing simulator coupled with an image generator. Results are presented, discussed and compared with a special focus on the performance over mountainous areas and filtering issues. Future indoor and experimental validation test benches are presented.

[1] Pham, B. V.; Lacroix, S.; Devy, M.; Drieux, M. & Philippe, C., *Visual Landmark Constellation matching for spacecraft pinpoint landing*, AIAA Guidance, Navigation and Control, 2009

[2] Mourikis, A. I.; Trawny, N.; Roumeliotis, S. I.; Johnson, A. E.; Ansar, A. & Matthies, L., *Vision-Aided Inertial Navigation for Spacecraft Entry, Descent, and Landing*, IEEE Transactions on Robotics, 2009, 25, 264-280