VISION BASED NAVIGATION FOR PROXIMITY OPERATIONS AROUND ASTEROID 99942 APOPHIS

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Abstract: *The work presented in the paper concerns the analysis of GNC techniques enabling autonomous operations around an asteroid at close range to characterize its gravity field. The paper focuses on the navigation aspects and analyses two concurrent vision based navigation methods (EKF-SLAM and recursive Bundle Adjustment) from accuracy, computational cost and robustness points of view. Robustness enhancement by the additional processing of laser range finder data and a priori knowledge is examined. Current results are synthesized and discussed.*

Keywords: *SLAM, Bundle Adjustment, EKF, navigation, asteroid*

1. Introduction

In recent years, there has been a growing interest in the space community for the Near Earth Objects and particularly the Potentially Hazardous Asteroids (PHA) which possible impact with Earth could be catastrophic given their size. CNES initiated in 2012 a mission concept study devoted to the scientific analysis of the asteroid 99942 Apophis in the perspective of its close encounter with Earth in April 2029. Among the various objectives that included the in-situ analysis on the surface with a dedicated lander, the determination of the asteroid gravity field added strong requirements on the vehicle maneuvering autonomy, in particular the capability to navigate for a long duration over the asteroid at very close range. The mission concept study was terminated in 2014 but internal R&D work was pursued in the guidance and navigation domain to assess the technical feasibility of the autonomous orbiting and landing operations.
So far, most missions to asteroids and comets have completely relied on ground analysts to perform the probe relative navigation with a few exceptions like JAXA's Hayabusa and NASA's Dawn. In particular, Dawn performed some on-board image processing to track specific features on the body surface using landmark maps previously generated by ground analysts. However, the need to reduce the tedious man-in-the-loop mapping process and increase the navigation robustness in case of large re-initialization uncertainties after a tracking loss is calling for techniques that can perform localization and also estimate the location of landmarks appearing in the field of view. Simultaneous Localization and Mapping (SLAM) that recursively estimates the vehicle state and the location of visual features through an Extended Kalman Filter represents an obvious candidate since it has become a very popular technique in the robotics field for wheeled mobile vehicles or UAVs. Recently, the Structure From Motion (SFM) approach that relies initially on batch optimization has been adapted into efficient sequential methods that perform bundle adjustment to extract the best localization and landmarks position fitting the observations. Previous studies showed that the sequential bundle adjustment (BA) approach could outperform EKF-SLAM in a large variety of conditions but the ability to detect non convergences remains an issue. The analysis described in the paper focuses on the navigation aspects and evaluates the relative merits of these two techniques for the Apophis "orbiting" scenario at close range.

2. Problem description and analysis

Characterization of an asteroid gravity field implies to navigate safely at close range during long periods of time and to measure accurately the probe motion fluctuations by radio science. Given Apophis characteristics, analyses have shown that this task imposes actuation free relative motions during tens of hours at a few hundreds of meters range which makes autonomous navigation mandatory. The envisioned solution is to insert and maintain the probe on a low terminator orbit representing the least unstable configuration since the orbital plane is normal to the Sun. On this orbit, the asteroid remains partly visible and mostly under a low incidence since the probe is flying over the night-day boundary.

The analysis focusing on the navigation techniques is performed under specific assumptions: (1) the probe carries a 45° x 45° FOV monocular camera with a resolution of 1000 x 1000 pixels, (2) the asteroid rotational motion is perfectly known (previously characterized by ground analysts), (3) the asteroid geometry is modelled as a rough ellipsoid with various sets of landmark distribution, (4) the trajectory is actuation free but submitted to Apophis and Sun gravitational fields, (5) the real gravity model is modelled with spherical harmonics of various amplitude, (6) the motion propagator assumes a simplified Apophis gravity model (homogeneous and symmetrical sphere), (7) attitude guidance assumes a perfect circular trajectory and provides a radial camera pointing.
To enhance navigation robustness, two additional options are also considered and compared with the previous solutions: (a) the probe carries a single laser range finder aligned with the camera line of sight and some low resolution model of the asteroid geometry is processed on-board, (b) a list of landmarks with coordinates defined in the asteroid reference frame is available

The paper describes the two navigation techniques implemented (monocular EKF-SLAM and recursive BA) and the add-on methods to enhance robustness by processing independently range measurement as well as a priori knowledge. Next, it details the analysis that is performed in three incremental steps:

1. image processing is simulated by a function providing measurements of the observable landmarks (modelled as points) assuming some Gaussian noise with ½ pixel standard deviation – the work based on Monte Carlo runs focuses on the comparison of EKF-SLAM and recursive BA considering the influence of parameters such as the image acquisition rate, number of landmarks and duration of visibility, number of keyframes and iterations involved in the BA optimisation process, amplitude of the force perturbation due to the gravity field uncertainty, initial state error ;
2. the previous setup is completed by introducing random outliers and some varying bias in the landmark measurement model to account for the shades evolution over time – the analysis focuses now on the navigation robustness and the algorithm ability to determine potential divergences: the benefit versus cost of processing additional data is examined for the two techniques and especially for recursive BA that does not deal explictly with uncertainty ;
3. image processing is introduced in the setup and applied on synthetic images produced with the 3D computer graphics **Blender** software - the asteroid visual aspect is made realistic by superimposing textures from Itokawa and Eros images on the artificially created 3D mesh – image processing is based on two types of feature detectors (Harris and ORB) – this step enables to consolidate the previous results in some end-to-end simulation scenario.