NEAR-INERTIAL HOVERING OPTICAL NAVIGATION AT THE CLOSE PROXIMITY OF VERY SMALL ASTEROIDS

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INTRODUCTION

Small bodies like comets and asteroids contain crucial information about the history of our solar system, making them particularly interesting targets of study by scientists. Recent developments extended spaceflight capabilities making these bodies available within our reach - especially those that travel close to Earth - opening new possibilities for exploration. Whereas missions as NEAR, Rosetta and OSIRIS-REx fly uncontrolled orbits where the spacecraft motion is mainly governed by the gravitational pull of the body, which is the dominating acceleration at the close proximity, this orbital approach is abandoned for very small asteroids or comets (<300m) [1-3]. The dynamics of a spacecraft near such a body are greatly complicated by the irregular mass distribution of these bodies, their weak gravitational fields, and the nontrivial perturbations due to solar tide, radiation pressure and manoeuver commands. One strategy that has been proposed to mitigate these difficulties is hovering nulling out the relative accelerations between spacecraft and body using the spacecraft thrusts. The Hayabusa mission used both the near-inertial hovering approach, with the spacecraft fixed in the Sun-NEO frame, and the body-fixed hovering approach, with the spacecraft fixed relative to the NEO [4]. Due to navigation and actuation errors, the spacecraft also maintains a mobility in the cross–track direction, be it with lower velocities. An additional challenge in this hazardous gravity environment is the demand for autonomoy increase as the round trip light time for spacecraft at the close proximity of NEO's can be up to 30min, complicating the intervention in case of emergency. Accurate relative state determination inherently contributes to a robust and secure hovering mode.

This work elaborates on the optical navigation between the 230m diameter, 1.4 elongation ratio NEO 2001 QC34 and a near-inertial hovering spacecraft located at a nominal 5km distance on the dayside. The scenario is illustrated in Figure 1, where the position of the S\C is controlled using an impulsive deadband control strategy. The guidance law restrict the spacecraft motion to a radial distance between 5150 and 6150m and limits the cross-track deviations to a 5° sun phase angle (SPA). A total of 3 manoeuvres are visible, with the nominal delta-v direction towards the Sun, i.e. away from the NEO surface.

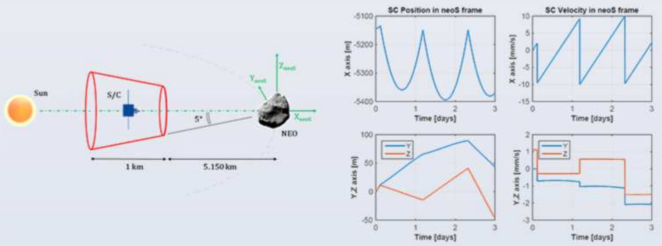

Figure 1: Near-inertial hovering

OPTICAL NAVIGATION DESIGN

The optical navigation (opNav) functional chain is shown below in Figure 2. The design is based on a database and camera image matching process. The navigation assumes that the mission has gone through a characterisation process where the NEO has been mapped using a laser altimeter (ALT) or Stereo Photoclinometry (SPC). The outcome is a NEO model with according landmarks, characteristic points on the surface. Both processes are iterative producing higher-fidelity shape models. An altimeter shape model is built from range measurements collected from the instrument and begins by generating low-resolution surface maps from a global set of ALT measurements or earlier telescope obervations. Using multiple images with different emission and incidence angles, SPC combines standard stereo techniques with photoclinometry, which derives the slope of the surface at each pixel [5,6]. This is a computationally intensive process, and a global shape model takes weeks, depending on the available processing assets and the targeted accuracy. SPC then uses the surface slopes to produce topography in local regions and then collates the local maps to produce a global shape model [5,6].

The database can be established in various ways. In this work, on-board camera images were used to link camera features to the NEO model landmarks. The OSIRIS-REx mission opted for a Natural Feature Tracking (NFT), an autonomous optical navigation software soute that renders Digitial Terrain Maps (DTM) catalogue [7]. The advantages of using camera images is the reduced need of a calibration, higher feature matching ratios and omits the necessity of rendering the NEO model, constraining the computational power ressources. NFT inherently offers a higher flexibility regarding the Sun-NEO-Camera illumination angles, which for near-inertial hovering conditions would be a limited asset.

An incoming image will be used to provide a new pose estimation by detecting and matching the features with the database entries employing an Euclidean normative procedure. An outlier rejection scheme applies the RANSAC algorithm and an additional pixel Euclidean norm to filter out corrupt matches. A perspective-n-point (PnP) algorithm solves for the camera pose by minimization of the non-linear reprojection error cost function. An outlier rejection scheme further filters pose estimations that are inconsistent with the expected measurement noise.

The state estimation algorithm is based on the extended Kalman filter (EKF) formulation which integrates the relative motions of equations (MOE) between the two bodies. The 12-DOF state vector contains the relative position, velocity and attitude of the spacecraft with respect to the NEO. The dominating solar radiation pressure (SRP) is also estimated. The spacecraft pose (position and attitude only) and accelerometer measurements are correcting the state vector, which is in turn provided to the dead-band impulsive controller.

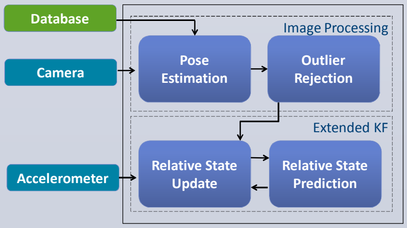

Figure 2: Optical Navigation Process Flow

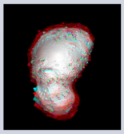

Figure 3: Cropped view of two images (cyan and red) captured by the camera. Most of the features are located the border of the small body where the surface contains more boulders. The features have an oblique radially outwards trend indicating a relative rotating movement of the near-inertial hovering S\C towards the NEO center of mass. Images generated with PANGU v4.01

RESULTS

The assumptions taken are perfect knowledge of the NEO pole direction, mass and spherical harmonics. No misalignment errors between the camera and the platform have been taken into account. For this work, the landmarks coordinate knowledges have been assumed conservately to a level of 1m (1σ) per axis in the NEO body fixed frame. Delta-v and accelerometer errors of 10% (3σ) were assumed. The performance simulations used synthetic generated images and were executed in a © MATLAB/Simulink environment.

Figure 4 shows the EKF estimated state covariances along with errors for 10 Monte Carlo runs for a scenario of 72 hours. The performance of the opNav is driven by the thruster errors, which detoriate the position and velocity knowledge at a rate of once per day, mainly in the NEO-Sun direction. The cross-track direction performance benefit from the higher observability and lower dynamics. With an absolute knowledge performance below 10m and 1mm/s, the maximum errors are bounded to 0.2% and 10% (3σ) in distance and speed. The attitude errors (expressed as Gibbs vector quantities) and SRP acceleration estimation errors are not influenced by the manoeuvres as the time constant of the attitude controller transients has been assumed smaller than the EKF sample frequency. The filter has been succesfully tested for consistency using the Normalised Estimation Error Squared metric [8].

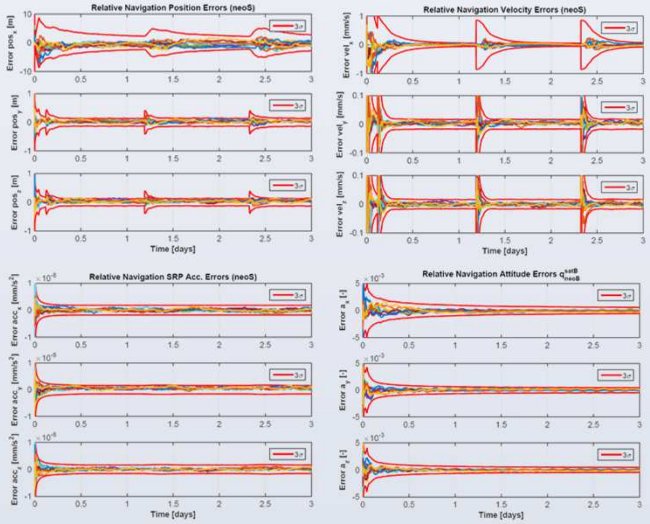

Figure 4: Optical Navigation performance reuslts for the scenario showing in Figure 1.

CONCLUSIONS

This work presented the optical navigation performance results for a near-inertial hovering spacecraft at the close proximity of a very small NEO. The optical navigation computational effort benefits from the restricted relative state variation in case of a near-inertial hovering motion and does not require rendering of the NEO model onboard the spacecraft. The relative position and velocity knowledge performance are driven by the actuation errors and stay below 10m and 1mm/s (3σ) in the line-of-sight direction, and below 1m and 0.2mm/s (3σ) in the directions parallel with the image plane. The relative attitude errors are limited to 1mrad (3σ) per axis. The solar radiation pressure acceleration is known up to 20nm/s^2 per axis. Further work shall first focus on the reduced knowledge of the NEO pole direction, mass and spherical harmonics. Also misalignment errors between camera and platform have to be taken into account. The attitude dynamics and settling times shall also be further investigated. Thereafter simulations on a microprocessor will assess the realtime performance and processor computation assets.

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ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant a greement No 640351.