Semi-autonomous navigation and gravity estimation around small bodies*

Julio C. Sanchez[1,2] and Hanspeter Schaub[2]

[1] Universidad de Sevilla, Sevilla, Spain
[2] University of Colorado Boulder, Boulder, United States
jsanchezm@us.es, hanspeter.schaub@colorado.edu

Abstract. This work tackles the problem of estimating the small body inhomogeneous gravity field. To this end, an unscented Kalman filter is combined with a batch least-squares method. Based on position measurements, the filter estimate the state and non-Keplerian acceleration. The navigation estimates are used to infer the spherical harmonics coefficients of the gravity field. Numerical results compare this method with the direct joint estimation of state and gravity within the filter.

Keywords: Autonomous navigation · Gravity estimation · Small bodies.

Small bodies exploration is a challenging task in terms of autonomous operations. The dynamical environment around a small body can be particularly complex due to its inhomogeneous gravity field, solar radiation pressure or the combination of both. Consequently, spacecraft operations have to be carefully designed so that undesired escape or collision trajectories are avoided. If the small body has enough mass, its low orbit regime (where hovering, landing or touch and go operations take place) is dominated by the inhomogeneous gravity field perturbation. While parameters such as the small body rotational state and its mass can be indirectly inferred from lightcurves and fly-by phase respectively, the inhomogeneous gravity parameters need to be estimated in-situ.

The current operational approach for small bodies gravity field estimation consists of gathering a huge number of observations to be processed on Earth. Then, the gravity solution is uplinked to the spacecraft. Overall, this constitutes a non-autonomous slow process. In that sense, developing autonomous gravity field estimation techniques could enable a faster exploration of these bodies. Several recent research works [1]-[3] have aimed in that direction. Both [1, 2] considered the joint estimation of the spacecraft state and inhomogeneous gravity parameters through an unscented Kalman filter (UKF). The benefit of multi-satellite formations, such as a close proximity swarm in [1] and a constellation in [2], were also analyzed. Ref. [3] used hopfield neural networks for simultaneous state and gravity estimation. Being sequential, the method is computationally efficient but the simulations were mainly limited to low order zonals.

* This work has received funding from the EU's H2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement THOR No 101025257.

Different from previous works, this research paper explores the possibility of combining the speed of a sequential method with the benefits of a batch one that allow to take into account past observations. In that line, based on relative position measurements, an UKF provides an estimation of the spacecraft state and the non-Keplerian acceleration. Consequently, position and gravity acceleration estimates are used to fit the spherical harmonics parameters in the least-squares sense. Then, the filter gravity is updated and the process runs recursively. Numerical results of this method are compared with respect to the joint state-gravity UKF estimation of [2] in terms of the global gravity solution accuracy, computational effort and trajectory propagation. The simulations are done using the Basilisk astrodynamics simulation framework [4]. An example of the global inhomogenous gravity estimation accuracy is shown in Fig. 1.

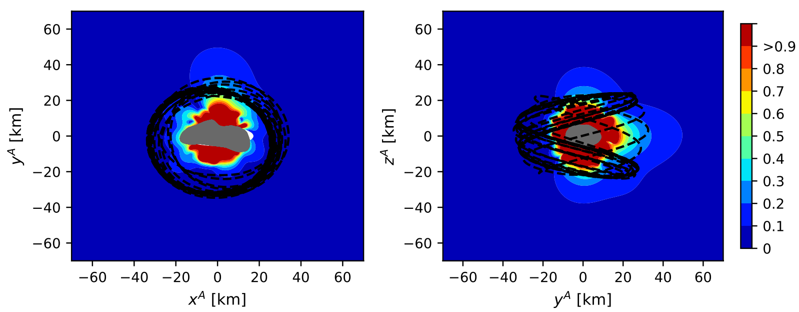

Fig. 1. Estimated inhomogeneous gravity error for 433 Eros. Black: trajectory.

Future work will aim to test the scalability and potential benefit of acquiring diverse data (e.g. multi-satellite [1, 2] or close to surface particles [5]). Transitioning the gravity inversion module to a neural network training in the spirit of [3] or directly representing the gravity as such (see [6]) could be of consideration.

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