Autonomous Visual Trajectory Reconstruction in the Proximity of Small Celestial Objects

Introduction

The effectiveness of a planetary defense response critically depends on the capability to react to threats in a timely manner. Maintaining a collection of baseline versatile tools requiring only adaptation and tuning is a possible approach to rapid countermeasures deployment. Focusing on autonomous navigation in the proximity of small celestial objects, in this work we present one such frameworks for trajectory reconstruction. This capitalizes on an extremely lightweight state-of-the-art visual localization algorithm, developed for targets well-approximated by a three-axis ellipsoid [1]. Whereas for small celestial bodies this might appear a weak approximation, our hypothesis is that apt acquisition strategies allow this nonspecific process to achieve operationally significant accuracies.

Methods

The study was performed in a developed prototyping environment named THALASSA (Figure 1), constructed using MATLAB [2] and Blender [3], a computer graphics toolbox. Path blocks are used to generate states of a nominal trajectory through a constant density three-axis ellipsoid gravity model. These are propagated to the Sensor blocks along with additional information to construct sequences of synthetic images, emulating the acquisition sequence of a probe moving in the proximity of a small rotating celestial object, in this case the asteroid Bennu. The probe's location is estimated using the lit limb of the target, detected within the visual data. This gets approximated by an ellipse and contextualized employing ephemerides and relative attitude information, assumed supplied through external sensors or artificial intelligence. Batches of these estimations are then employed to reconstruct the orbit of the spacecraft in a chosen gravitational model using a nonlinear least square filter correcting an initial reference orbit.

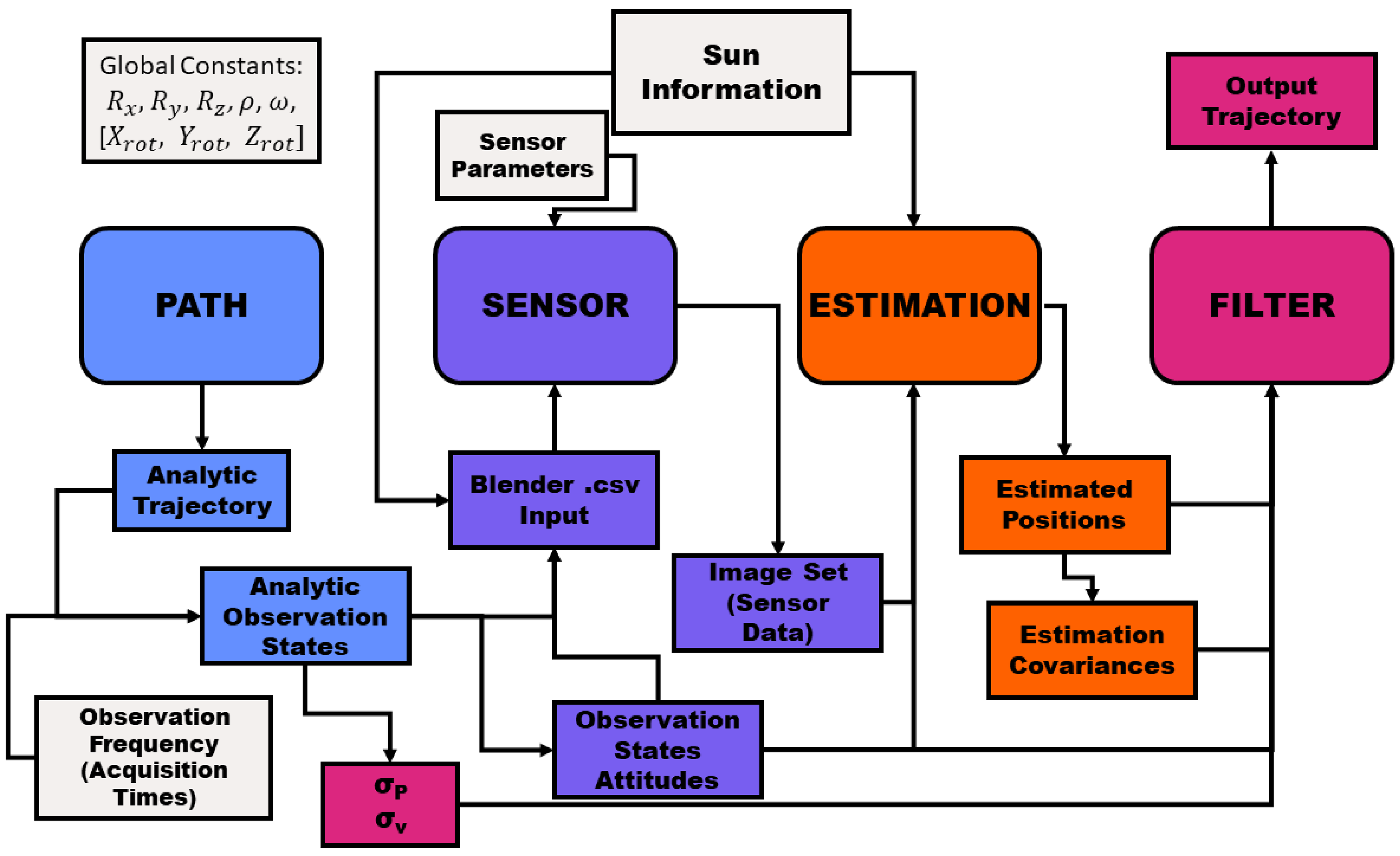

Figure 1 – The structure of THALASSA (Technologies for Hazard Avoidance and Landing for Autonomous Spacecraft with Situational Awareness)

Results

The analysis revealed a high sensitivity of the estimation process to the solar phase angle, the target-relative pose of the probe, and their coupling. Mapping the response for a center-pointing probe highlighted critical acquisition regions, as eclipse conditions or the planes generated by the largest semi-axes of the asteroid. The former was exploited to create a heuristic filter to detect and remove outlying estimates, improving the estimation accuracy and robustness.

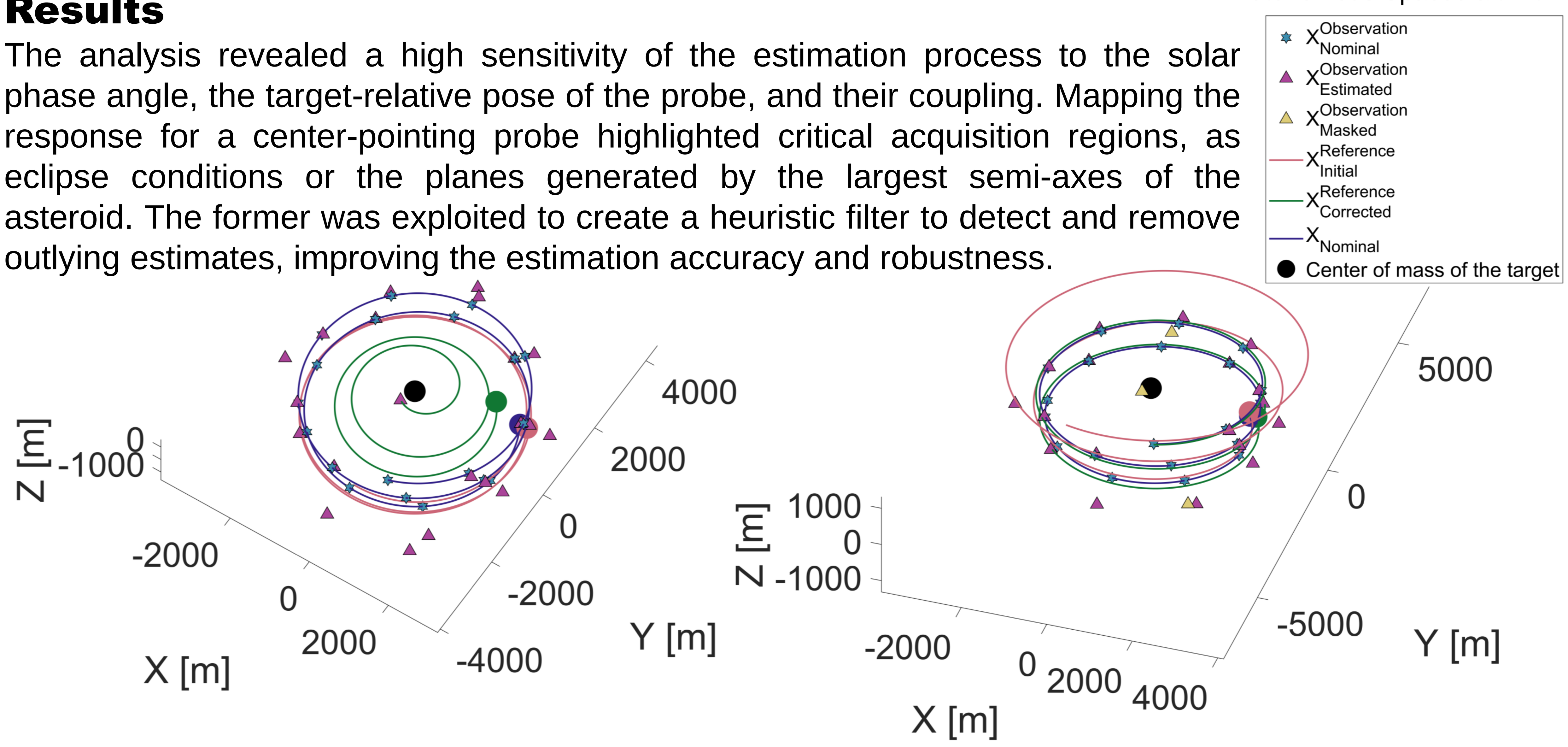

Figure 2 – Two orbital reconstruction processes with the same circular nominal trajectory ($R = 2480\ m$). The one of the left uses every observation; in the other, the ones with a Sun phase angle $> 150°$ were discarded. The sampling frequency is $\Delta t = 0.5\ h$

As a test, let us retrieve an initial corrected state, both with and without points in eclipse (defined as having Sun phase angle $> 150°$) and propagate it to $t_{end} = 10\ h$. By removing only three eclipse points it is possible to shift the 1σ (300 samples) of the position error at t_{end} from $2041\ m$ to $59.6\ m$ (Figure 2). Figure 3 shows the comparison of a good fitting to an ellipse and a bad one.

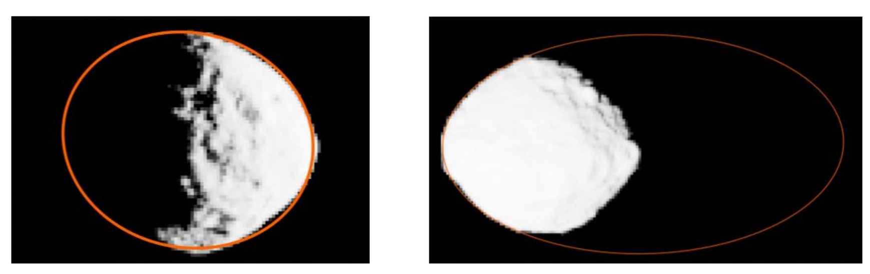

Figure 3 – On the left a good acquisition; on the right an Equatorial acquisition leading to a large error.

Conclusions

We showed that it is possible to perform trajectory reconstruction with small uncertainties using a computationally light autonomous navigation method not optimized for irregular objects. by implementing apt acquisition and data rejection strategies. This can enable autonomous operations in complex, uncharted environmental conditions for resource constrained platforms.

References

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