Design and Simulation of High-Accuracy Star-Trackers Algorithms for Autonomous Line-of-Sight Navigation.*

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Deep-space CubeSats are becoming a valuable alternative to common spacecraft. Their exploitation can mark a new era in space exploration, broadening the possibilities for many space-sector players, due to the evident cut down of the mission's cost. For a proper exploitation of miniaturized probes, autonomous navigation is a necessary pillar. In this framework, Line-of-Sight (LoS) navigation represents a valuable option for state estimation during deep-space cruising.

LoS navigation is an optical technique, based on the observation of visible celestial objects (e.g. planets), whose ephemeris are sufficiently known. The directions of these bodies is obtained with on-board optical instrumentation, either cameras or star-trackers, and it is compared within the navigation filter with their actual position, retrieved by on-board stored ephemeris. The possibility of performing on-board the complete estimation procedure, makes the technique a valid candidate for autonomous deep-space CubeSats. Navigation accuracy especially depends on two characteristics: the observation geometry and the LoS direction extraction accuracy [1]. The first depends on the mission scenario, which defines the visible bodies and their relative geometry. The second depends on the imaging hardware, the image processing algorithms, and again the mission geometry. Despite the mission can be slightly adjusted to occur during a favourable observation geometry window [2], often it is not sufficiently flexible to increase the estimation accuracy. For this reason, the LoS direction extraction accuracy is playing a crucial role in the overall navigation performance. In this context, this work is aimed to properly generate synthetic star-trackers images, which are then used to test the performance of designed LoS extraction algorithms.

The generation of synthetic images depends on the characteristics of the imaging sensor and lenses. For star-trackers, a pinhole camera model is assumed. The Hipparcos-2 catalogue is used to retrieve the directions of visible stars, which are converted in the sensor reference frame. The stars visual magnitude is converted in the number of photo-electrons read on the sensor array. This conversion depends on sensor's characteristics (pixel size, fill factor, quantum efficiency), lenses diameter, and exposure time. To reach sub-pixel accuracy in the star centroiding algorithm, the incoming light is deliberately blurred, so the information is spread over different pixels. This is simulated with a Gaussian distribution. Simulation of planets is less straightforward, as both shape and apparent visual magnitude depend on the observation geometry. To properly

* funded by the EU H2020 MSCA ITN Stardust-R, grant agreement 813644.

represent the shape of the observed object, the ray-tracing method presented in [3] is exploited. The method is then improved, by simulating the the Sun shadow information. To simulate accurately the shape of the object, each pixel in the area around the object is partitioned in a 10 by 10 sub-pixels grid. Then the intensity of the actual pixel is obtained by summing up the set of corresponding sub-pixels. Differently from stars, planetary magnitude cannot be considered constant, but it can be expressed as a function of the relative geometry. Each planetary magnitude is characterized by a specific formula [4]. Then, the magnitude value is again converted in photo-electrons number. Finally, on-top of the image, background noise is added, and analog to digital conversion is simulated.

Star-trackers algorithms are then designed. Attitude estimation chain is based on image scanning, de-noising, star centroiding, star identification, and Wahba's problem solver. Star trackers operating in highly dynamic conditions require a trade-off between algorithm accuracy and speed. In a deep-space cruising application, due to the more static attitude characteristics, it is possible to sacrifice algorithm's speed to achieve a higher accuracy. This reflects in the choice of a Least Squares Gaussian Fitting star centroiding algorithm, which takes longer running times with respect to common center-of-gravity methods, and in the choice of larger scanning phase in order to identify a larger number of stars. In fact, in a simplified simulation frame, the impact on the attitude estimation performance of centroiding accuracy and number of stars is shown. Then, stars identification is performed, based on the relative geometry matching with triplets of stars, and the final attitude estimation subroutine is based on a SVD method. The planet centroiding is based on a weighted center-of-gravity method, corrected by the information on the Sun-light direction. To further improve the performance of the LoS extraction, an observation strategy is proposed. Thanks to the slower-changing attitude condition of the observation, a set of larger exposure time images is taken, in order to compute with higher accuracy the center of the stars in the FOV. With the superimposition of subsequent image frames, centroiding accuracy improves significantly. Then, as planet brightness usually saturates several pixels, to improve LoS extraction accuracy, a lower exposure time image is recorded, and then the images information is merged. Finally, algorithms are tested with synthetic images, and performance is highlighted.

References

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