Combined Crosslink Radiometric and Optical Navigation for Distributed Deep-Space Systems.*

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In the deep-space exploration framework, the use of distributed space systems is gaining popularity. Their applicability to a wide range of deep-space scenarios is currently under investigation, ranging from planetary to small-bodies missions. A valuable example is represented by the NEACORE mission concept, which proposes Near-Earth Asteroids fly-by with a pair of CubeSats [1].

Autonomous navigation needs to be considered as a pillar for miniaturized deep-space missions. While the attention is often focused on autonomous navigation around a planet, a moon, or a small-body, deep-space cruising autonomy is similarly important, especially in connection with the current trend of autonomous on-board guidance [2].

In this context, this work is intended to show the characteristics of a combined crosslink radiometric and optical navigation for pairs or swarms of interplanetary cruising CubeSats. Despite the attention is focused on miniaturized satellites, the applicability can be extended to larger mission architectures.

Crosslink radiometric navigation is an autonomous orbit determination method, only based on satellite-to-satellite measurements, such as range and/or range-rate. Its applicability to relative navigation around bodies has been proved, such as in the Cislunar space [3]. Very high accuracy has been showed in various scenarios. However the method produces noteworthy results especially when the two (or more) satellites belong to sufficiently different orbits, while performance degradate when the dynamical characteristics of the satellites are similar. The latter is indeed the case for interplanetary cruising spacecraft, which fly towards the common target in sufficiently similar dynamical conditions. For this reason, the exploitation of the only crosslink radiometric navigation is not sufficient to guarantee an accurate state estimation.

On the other hand, Line-of-Sight (LoS) navigation represents as of today the higher performance autonomous method for the state estimation of an interplanetary cruising spacecraft. It is an optical navigation technique, based on the observation of visible celestial objects, mostly planets, whose direction is matched with their actual position, retrieved by on-board stored ephemeris. The LoS direction is obtained on-board by means of dedicated cameras and/or star-trackers. The technique is strongly dependent on the geometry of the problem. To obtain an accurate estimation, the observation of at least two objects (e.g. planets) is needed [4]. This has a clear impact on both the the spacecraft system design, and the navigation strategy. It implies that either multiple imagers

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are necessary on-board, to observe simultaneously different objects, or, in case of a single available camera, slew maneuvers are needed to center sequentially different objects in the Field-of-View. Both alternatives are not fully compatible with miniaturized spacecraft, as multiple cameras imply larger volume and mass, while similarly, a large number of slew maneuvers (only for navigation purposes) may increase significantly the required on-board propellant, for both wheels de-saturation and/or actual maneuvers.

In this framework, a combined crosslink radiometric and LoS navigation approach appears to be promising for distributed space systems, in particular for a swarm of interplanetary cruising spacecraft. Intersatellite communication instrumentation is necessary for various operations and can be re-used for navigation purposes, while the number of necessary cameras, maneuvers, and logistic operations for LoS navigation can be simplified and reduced. An Extended Kalman Filter formulation is presented to estimate the state of each spacecraft, and Monte Carlo simulation are exploited to show the applicability to realistic mission scenarios. First, as an example, the combined navigation technique is applied to the trajectory of the two JPL MarCO-A and MarCO-B CubeSats, which as of today represent the only pair of miniaturized satellites which travelled in deep-space. Then, in a more general context, some NEAs mission examples are analyzed to generalize the results. Swarm of two, three, and four satellites are considered, with a various number of planet observation and crosslink radiometric architectures. All of the simulations are based on characteristics of CubeSat hardware, which impact the definition of the simulated error on the measurements.

Results are compared among each architecture, and the applicability of this method is proved, highlighting comparable navigation performance with the case of a single satellite equipped with multiple cameras.

References

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