Autonomous Far-Range Vision-Based Rendezvous with a Target Space Object

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Motivation

Future missions involving the interaction of multiple satellites present increasingly demanding relative navigation requirements which must be achieved autonomously using limited onboard resources. Vision-based navigation techniques deliver an effective response to these needs by providing an inherently passive, robust, and high-dynamic range capability which uses simple sensors that are already on board most spacecraft. Furthermore, because of their low cost, low power consumption, and small form factor as compared with other metrology systems, these sensors enable accurate relative navigation while complementing the current trend of spacecraft miniaturization.

Challenges and State-of-the-Art

This research focuses on the far-range angles-only relative navigation problem, where an observing spacecraft uses a set of bearing angles to determine the relative orbital motion of a target. In this scenario, constrained dynamical observability makes it difficult or impossible to estimate the full 6D relative state from sequences of 2D measurements. A common solution is to conduct known orbital maneuvers to change the bearing angle trends, but this has the undesired effect of strongly coupling the maneuver-planning and navigation tasks. Finally, nearly all existing research studies are confined to near-circular orbit applications.

Maneuver-Free Angles-Only Navigation

Research goal: Enable accurate and robust angles-only estimation of the target’s relative motion in arbitrarily eccentric orbits, without requiring reconfiguration maneuvers for observability improvement.

Design strategies for responding to the challenges:

• Parameterize relative orbital motion using mean Relative Orbital Elements (ROE): \( \delta x = (\delta a, \delta h, \delta e, \delta h, \delta i, \delta r) \). This choice allows relevant perturbations like \( J_2 \) and atmospheric drag to be seamlessly included in the dynamics. Furthermore, the weak observability is largely decoupled to one element (\( \delta h \)).

• Improve dynamical observability by exploiting the nonlinearities relating mean ROE to osculating ROE in the Unscented Kalman Filter measurement model. The osculating ROE short-period oscillations encode separation-dependent features (see figure below) that disambiguate the weakly observable range.

• Supplement reduced onboard dynamics model with adaptive process noise tuning online using an innovation-covariance matching technique. By improving the process model, measurement trends observed by the sensor are assimilated into improved state estimates.

• Derive method for angles-only initial relative orbit determination for accurate filter initialization in eccentric, \( J_2 \)-perturbed orbits.

Oscillating (blue) and mean (red) ROE trends beginning from initial conditions (K and O markers, respectively). Mean separation varies from -20 km to 0 km.

References


Navigation Algorithm Verification

Angles-only navigation algorithm verification architecture using the optical stimulator testbed with far-range camera in the loop.

ROE estimation errors and 1-sigma bounds using an adaptive UKF. Measurements are obtained from a far-range navigation camera in the loop. Relative trajectory approaches from 20km down to approximately 5km in near-circular low Earth orbit.