Autonomous Multi-Observer Angles-Only Navigation for Spacecraft Swarms around Planetary Bodies

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This paper presents and demonstrates a new algorithmic framework for autonomous angles-only navigation of spacecraft swarms around planetary bodies. Angles-only navigation, in which cameras aboard observer satellites within the swarm provide bearing angles to target space objects, is compelling as it reduces reliance upon Global Navigation Satellite Systems and thus enables new swarm mission concepts in deep space scenarios. However, existing angles-only methods in literature face significant limitations – they typically handle only one observer and one target, and rely on regular ground support (for repeated re-initialization) and translational maneuvers (to resolve target range ambiguity). To overcome these limitations, we present a novel angles-only navigation architecture called the Angles-only Relative Trajectory Measurement System (ARTMS) which applies multiple observers to enable robust swarm navigation.

Three contributions to the state-of-the-art are presented. First is a quantitative observability analysis of multi-observer angles-only navigation in Mars orbit, via computation of the state covariance using a measurement noise matrix (representative of expected sensor performance) and a bearing angle sensitivity matrix across all measurement epochs. The estimated swarm state consists of the observer absolute orbit, target relative orbits, and differential clock drifts and drift rates between observers. The resulting sensitivity matrix is full-rank for all investigated scenarios due to the nonlinearity in the J2-perturbed analytical dynamics model. For a four-spacecraft formation in which all spacecraft observe all others, the complete state is observable without maneuvers or regular ground contact: after two orbits, the absolute orbit is estimated to 600m, target ranges are estimated to 0.1%, and other relative state components are estimated to 0.01% of target range. Clock drifts are estimated to within 1.5s. For in-train formations, target range estimation errors are up to 3%. Second, a new multi-observer measurement assignment algorithm is described, whereupon observers use local relative orbit estimates or remote observers’ absolute orbit estimates to consistently match local and remote measurements. Third, we validate the estimation accuracies from the observability analysis through simulations of angles-only navigation in Mars orbit using ARTMS. ARTMS is a software payload that will be flown on the upcoming NASA Starling1 mission and consists of three modules: Image Processing (IMP), which identifies and computes bearing angles of targets in camera images; Batch Orbit Determination, which computes a swarm state initialization from IMP measurements; and Sequential Orbit Determination, which uses an unscented Kalman filter to navigate after initialization.

For a simulated four-spacecraft formation with four observers, using synthetic image measurements with a 50% eclipse period, ARTMS achieves accuracy in line with the observability analysis. After two orbits, the absolute orbit is estimated to 800m, target ranges are estimated to 0.15%, and other relative state components are estimated to 0.01% of target range. Hardware-in-the-loop results using a CubeSat star tracker and flight processor display comparable performance. Overall, these analyses demonstrate autonomous, high-dynamic-range navigation with low volume, mass and power requirements; no ground intervention after initialization; and no reliance on maneuvers. ARTMS is therefore considered a promising solution for missions aiming to apply spacecraft swarms and their advantages in deep space environments.