Robust Spacecraft Swarm Design using Generalized E/I-Vector Separation

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While most formation flying missions to date employ a pair of satellites, there is growing interest in larger swarms of spacecraft. Indeed, proposed mission concepts such as the Silicon Wafer Integrated Femtosatellites (SWIFT) call for hundreds to thousands of spacecraft [1]. A promising approach to designing such swarms is the concentric passive relative orbit approach proposed by Morgan [2]. However, the described guidance, navigation, and control (GN&C) architecture requires computationally expensive numerical optimizations and sensors and actuators that are not readily available for small spacecraft. To address these concerns, this paper presents a new design methodology for spacecraft swarms using relative orbital elements (ROE). The key contributions of this paper are as follows. First, relative orbits that minimize the evaporation caused by J_2 and differential drag are derived from recently developed state transition matrices for perturbed relative motion. Next, D'Amico's relative eccentricity/inclination (E/I) vector separation concept [3] is generalized to ensure passive radial/cross-track separation between all spacecraft in a swarm. Combining these results, swarm geometries are identified that guarantee weeks of passive safety and predictable motion under the effects of J_2 and uncertain differential drag. An example swarm design is illustrated in Fig. 1. However, without active control the radial/cross-track separation of the swarm will collapse once every few weeks due to precession of the argument of perigee. Because orbit precession is predictable, a hybrid passive/active nonlinear control law is developed that satisfies a new set of collision avoidance constraints in the radial/along-track plane when passive separation perpendicular to the flight direction is not guaranteed and otherwise lets the swarm freely drift. This control law reduces the mean along-track separation to zero in a specified time at the minimum possible delta-v cost. Additionally, actuation is only required in the (anti-) flight direction and can be implemented with thrusters or differential drag control. Furthermore, this approach only requires the state of each spacecraft to be estimated with respect to a single common reference, such as a mothership, and not between each pair of spacecraft, reducing computational load on the GN&C system. Finally, the proposed swarm designs are validated through simulations using a high-fidelity numerical orbit propagator. It is found that the proposed swarm designs provide months of safe, bounded relative motion for a swarms of hundreds of spacecraft with total delta-v costs of no more than a few meters per second per spacecraft even when realistic GN&C considerations such as navigation and control errors and atmospheric drag uncertainty are included. Overall, the proposed methodology simplifies the swarm design problem, providing robust passive safety using minimal computational resources and control effort.

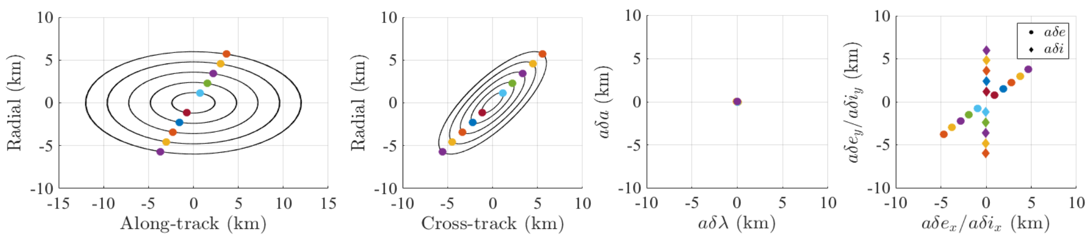

Fig. 1: Swarm configuration with passive collision avoidance via generalized E/I vector separation in relative position (left) and ROE (right) spaces.

References

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