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A PARTICLE SWARM OPTIMIZATION FRAMEWORK FOR A DEBRIS-TRACKING SATELLITE CONSTELLATION

Abstract

The growing accumulation of space debris in Low Earth Orbit (LEO) poses a significant risk to operational satellites, space missions, and the long-term sustainability of space activities. Traditional ground-based tracking methods are limited in their ability to detect small debris (>1 cm in average diameter), necessitating the deployment of space-based constellations for real-time detection, tracking, and cataloging of orbital debris. However, designing an optimal satellite constellation for maximum LEO coverage and efficiency presents a complex challenge due to trade-offs between orbital configurations, instrumentation requirements, cost and power constraints.

This study employs Particle Swarm Optimization (PSO) to determine an optimal constellation configuration for satellite-based space debris monitoring. Specifically, the baseline system designed for and used in this work relies on high-resolution electronically-scanned phased array radars, which demand significant power and advanced data processing capabilities, making orbital optimization a critical factor alongside systems design. A physics-based debris field simulation, leveraging data from the ESA MASTER model, was integrated with a GPU-accelerated constellation benchmark into a scalable, adaptable PSO framework that efficiently evaluates and refines constellation designs. Key optimization variables included orbital inclination, eccentricity, right ascension of ascending node (RAAN), and satellite distribution, with a Gaussian Mixture Model (GMM) used to adaptively allocate satellites based on debris density distributions.

Early results indicate that an equatorial, circular-orbit configuration maximizes detection efficiency, aligning with regions of peak debris concentration; however this configuration also increases collision probability in longer-term missions. Optimized constellations scored a 2-3x efficiency improvement in debris detection over baseline configurations, demonstrating the effectiveness of the PSO-drivenapproach.