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COLLABORATIVE POSITIONING FUSION FOR PRECISE NON-COOPERATIVE SPACE DEBRIS SURVEILLANCE AND TRACKING IN CONSTRAINED SENSING ENVIRONMENTS

Abstract

The rapid accumulation of space debris gives an increasing threat to operational satellites and future space missions. When space robots offer promising solutions for debris removal, the effective capture of non-cooperative debris requires precise positioning accuracy under severely constrained sensing conditions. Traditional relative vision sensors face the problems of dependence on ambient light, celestial occlusion and field of view limitations. In this paper, we introduce an innovative collaborative sensing fusion framework that enables multiple space robots to jointly execute precise debris tracking task even in adverse environments. Our approach leverages a distributed sensor network in which agents dynamically share complementary measurement data via crosslink ranging and time-synchronized observation fusion. Each robot is equipped with different sensors, such as CCD cameras, LiDAR, and TOF, whose measurements are integrated within a cooperative estimation framework. Central to our system is a federated information filter that optimally fuses heterogeneous sensor data while accounting for communication delays and bandwidth constraints inherent in space operations. Furthermore, we propose a novel distributed estimation algorithm that exploits relative measurements between agents to enhance cooperative localization robustness against individual sensor failures. An adaptive measurement gating mechanism, underpinned by contextual confidence scoring, is employed to identify and mitigate real-time perception challenges. Simulation results validate that the proposed collaborative architecture achieves sub-meter-level positioning accuracy and sub-degree attitude determination for debris objects, even when individual sensors are compromised by adverse sensing conditions. This research not only advances space-based navigation capabilities for complex orbital operations but also lays the groundwork for fully autonomous debris removal missions, contributing to long-term space sustainability.