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# COLLISION RISK ASSESSMENT AND AVOIDANCE METHODS FOR SAFE AUTONOMOUS PROXIMITY OPERATIONS

**Abstract**

Recent advancements in the in-orbit servicing domain have intensified the need for robust strategies to enable safe and efficient satellite proximity operations. Developments of servicing and debris removal missions are critical to ensuring the long-term sustainability of space activities from both environmental and economic perspectives. A primary challenge in these operations lies in balancing high levels of autonomy with stringent safety requirements. Autonomous systems must not only operate independently but also demonstrate resilience to a broad spectrum of potential failures. This paper presents novel techniques for enhancing the safety modules of proximity operation missions—key enablers of robust Guidance, Navigation, and Control (GNC) systems to guarantee autonomy. The first focus of this work is the development of collision risk metrics tailored for autonomous proximity operations. Specifically, we introduce metrics that estimate the collision risk—or establish reliable bounds on it—over defined time intervals for objects on neighboring orbits. These metrics allow for real-time modeling of failure trajectory evolution, facilitating informed and proactive mitigation strategies. Our proposed collision metric leverages an analytical approximation of the distance between the two objects uncertainty distributions. This approach is systematically compared with existing methods in the literature, including Mahalanobis distance, geometric Cartesian distance, and collision probability metrics adopted for debris encounters. The analytical nature of our approach, combined with a linear relative motion model for state and uncertainty propagation, delivers a significant computational advantage. This efficiency makes the method particularly suitable for autonomous onboard implementation and rapid decision-making specific for proximity operations. Secondly, this work addresses the autonomous planning of collision avoidance maneuvers (CAMs), leveraging closed form solutions of the impulsive controlled relative motion. Our approach is also suitable for onboard CAM computation in scenarios with constrained control authority, such as those involving partial thruster failures. The collision avoidance strategy, whether a single maneuver or a sequence of maneuvers, is formulated as a convex optimization problem. The optimization framework balances promptness and fuel efficiency, computed taking into account the cost of reestablishing the formation once that the contingency has been recovered. The performance of the developed methodologies is rigorously evaluated through numerical simulations. The challenging scenario of a forced-motion close-range rendezvous is emphasized, analyzing a range of failure conditions. The results demonstrate the robustness and adaptability of our approach, highlighting its potential to enhance safety and autonomy in future proximity operations missions.