Optimal planning for a multiple space debris removal mission using high-accuracy low-thrust transfers

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ABSTRACT

Lower Earth orbit (LEO) contains a significant number of large space debris, primarily consisting of defunct spacecraft and rocket bodies as well as fragments thereof, which are at risk of colliding with working satellites or other debris. Furthermore, spacecraft launches into LEO are occurring at an increasing rate. As such, for the continued safe utilization of space capabilities in LEO, active debris removal (ADR) has become a topic of intense research for future space missions. Indeed, several demonstration experiments have already been carried out in space. One emerging consideration for ADR missions is the possibility of removing multiple pieces of debris in a single mission. Multiple debris missions are not only important from a financial perspective but also from a timing perspective, especially if five pieces of debris are to be removed within one year. In fact, for this to be a realistic goal on a consistent basis, the implementation of multi-debris removal missions is a necessity, not an option.

The purpose of this research is to evaluate and minimize the fuel and time cost of the accurate rendezvous and the de-orbiting of multiple pieces of space debris in a single mission. Continuous low thrust maneuvers are used to achieve each orbital transfer. The mission scenario considered requires the chaser to capture and de-orbit the debris into a disposal orbit, after which it releases the first piece of debris and performs a rendezvous with the next piece of debris in a recursive fashion. This approach is well suited for capture methods resulting in a flexible connection between the chaser spacecraft and the debris.

Within each rendezvous phase, the orbital drift of both the chaser and the target are considered. This is done in order to ensure the orbital elements of the chaser are matched to the actual location of the debris at the end of the maneuver. Modified equinoctial elements are used to define the equations of motion of the chaser and two-line-element data is used to define the initial location of the debris. For scenarios where the difference in Right-Ascension-of-the-Ascending-Node (RAAN) between two pieces of debris are deemed too large, an optimized drift orbit is selected in order to naturally change the RAAN of the chaser to match that of the debris. Each maneuver is defined as a minimum- time orbital transfer, using low thrust propulsion and the transfer posed as a constrained non-linear optimal control problem, implemented in GPOPS-II. The initial guess for the transfer time constitutes the period over which the given piece of debris is propagated to find the location of the debris after transfer. The location of the debris is then used as an initial guess for the final boundary constraint of the high-accuracy transfer. This procedure is performed in an iterative manner until the post-propagation location of the debris matches the location of the chaser following the high-accuracy transfer, within certain error bounds.

Two sets of five debris have been selected for demonstrating the proposed methodology—both situated in lower Earth orbit. The outcome is the best possible trade-off between time and fuel for the multiple-debris removal mission and the transfer characteristics required to achieve it.