Application of Multi-Agent Coordination Methods to the Design of Space Debris Mitigation Tours

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Keywords: *automated trajectory design, multi-agent coordination, space debris mitigation, vehicle routing problem*

ABSTRACT

The current population of debris objects in Earth orbit and the projected growth of the size of this population is an increasing threat to existing and future on-orbit assets. Debris objects pose a hazard to active spacecraft, often necessitating maneuvers to avoid dangerous close approaches, while collisions between inert objects have the potential to create a cascading build-up of debris in near-Earth orbit, where this Kessler Effect could severely restrict the potential of future missions. Indeed, in February 2009, an on-orbit collision occurred between an active Iridium communications satellite and a defunct Cosmos satellite wherein the Iridium satellite was lost and large amount of new debris objects were released. At the same time, active anti-satellite system tests, such as the Fengyun-1C and USA-193, have contributed significantly to the debris environment. The Fengyun-1C test was particularly disruptive as it generated a large amount of debris in an already relatively highly-populated orbit. Accordingly, satellite disposal policy and active debris removal campaigns are a focus of international discussion and investigation.

Active campaigns to remove notably larger and particularly hazardous debris objects, such as expended upper stages from launch systems or debris crossing the orbit of the International Space Station, have the potential to slow and even reverse the growth in the debris population and reduce the hazard posed to existing assets. The design and operation of debris mitigation missions is complicated by the wide range of orbits occupied by the debris objects and the differing physical characteristics of the objects themselves, for example size, mass, and shape. On the other hand, many similarly constituted high value targets within the debris population occur in distinct orbital groupings in the vicinity of Earth and, thus, possess a higher likelihood of presenting tour opportunities that encounter a relatively large number of similar objects. Consider, for example, the 22 empty upper stages of the SL-16 / Zenit-2 launch system residing in approximately circular 850-km altitude orbits, as illustrated in Fig. 1. The orbits of these objects appear in two distinct groups at roughly 71° and 98° inclination and are primarily distinguished by differences in the right ascension of the ascending node (RAAN). A significant fraction of these 22 rocket bodies could be mitigated by a relatively small number of multi-year missions, and a quicker removal strategy, if a larger number of mitigation spacecraft are

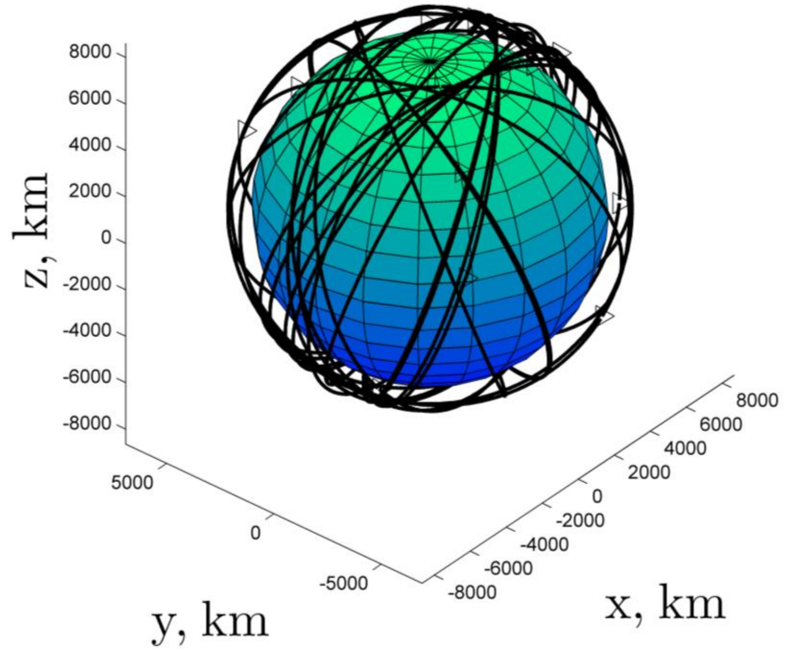

Figure 1. Orbits of 22 depleted upper stages of the SL-16 / Zenit-2 launch system. Triangles indicate the position of the rocket bodies at 12:00pm, July 4, 2013, UTC.

employed. Likewise, mitigation of larger portions of the debris population necessitates a supporting infrastructure involving "servicer" or "chaser" spacecraft.

Debris mitigation mission design scenarios for a single servicer spacecraft are often modeled as a vehicle routing problem (VRP) or minimum latency problem (MLP) where the goal is for the spacecraft to encounter and mitigate a large number of debris objects while constrained by the available propellant. Challenges posed by the single spacecraft scenario, while not insignificant, will be addressed using a novel tour design scheme that exploits several positive features of low-thrust propulsion systems. On the other hand, as a single servicer will only be able to encounter a limited number of debris objects and is usually limited to addressing a specific type of debris object, a framework involving multiple mitigation spacecraft will be required to effect a significant reduction in the debris population, even if the target bodies are of similar physical composition. The design of single spacecraft tour missions is in itself an extremely difficult, i.e., NP-hard, problem with a design space that scales exponentially with the inclusion of additional targets. The simultaneous design of multi-spacecraft tours adds a further exponential growth to the design problem. Further complications to the design process include an organizational structure whereby the operation of the chaser spacecraft that can be simultaneously controlled or distributed in time as well as multiple spacecraft could be operated by different, possibly competing, agencies or companies. Accordingly, multi-agent coordination methods such as auction algorithms are investigated and applied to the generation and operation of multiple debris mitigation tour trajectories. Furthermore, existing solution methods to the vehicle routing problem, such as "ant colony" optimization, are modified for suitable inclusion within a multi-agent design model. These multi-agent, heuristic methods offer the potential to rapidly and adaptively generate a set of nearly-optimal tour scenarios that coordinate the actions of multiple servicer spacecraft with the goal of reducing the overall hazard posed by the debris population.