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Biobjective planning of GEO debris removal mission with multiple servicing spacecrafts

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ABSTRACT

The mission planning of GEO debris removal with multiple servicing spacecrafts (SScs) is studied in this paper. Specifically, the SScs are considered to be initially on the GEO belt, and they should rendezvous with debris of different orbital slots and different inclinations, remove them to the graveyard orbit and finally return to their initial locations. Three key problems should be resolved here: task assignment, mission sequence planning and transfer trajectory optimization for each SSc. The minimum-cost, two-impulse phasing maneuver is used for each rendezvous. The objective is to find a set of optimal planning schemes with minimum fuel cost and travel duration. Considering this mission as a hybrid optimal control problem, a mathematical model is proposed. A modified multi-objective particle swarm optimization is employed to address the model. Numerous examples are carried out to demonstrate the effectiveness of the model and solution method. In this paper, single-SSc and multiple-SSc scenarios with the same amount of fuel are compared. Numerous experiments indicate that for a definite GEO debris removal mission, that which alternative (single-SSc or multiple-SSc) is better (cost less fuel and consume less travel time) is determined by many factors. Although in some cases, multiple-SSc scenarios may perform worse than single-SSc scenarios, the extra costs are considered worth the gain in mission safety and robustness.

1. Introduction

The geostationary ring is a valuable resource and the monotonically growing debris population in the Geosynchronous Equatorial Orbit (GEO) increases the probability of accidental collision with known objects during the system's orbital lifetime [1–3]. Even though there are mitigation measures in favor of moving satellites at end of life to a graveyard zone above the densely populated geosynchronous ring [2], there are still many nonoperational satellites in geosynchronous orbit that are a hazard to other satellites. In addition to mitigation measures, the active removal of non-operating spacecrafts will be mandatory to stabilize the critical regions of GEO. The Active Debris Removal (ADR) scenario in this study presupposes a dedicated servicing spacecraft (SSc), which is launched from Earth, and performs rendezvous and docking maneuvers to finally re-orbit multiple targets.

Essentially, ADR is a multi-spacecraft rendezvous mission. Despite the success in servicing a single spacecraft [4] and the numerous papers studying optimal rendezvous between two spacecrafts (e.g. [5,6]), so far there has been only a little reported work devoted in the area of developing optimal sequence and trajectories for ADR. Alfriend [7] tried to determine the minimum fuel solution for visiting a set of satellites in GEO with small inclinations. His method focused on minimizing the fuel required for the plane changes.

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In [8], chemical and electric propulsion systems were analyzed with the main focus on removing multiple debris within one single mission. In [9], based on Space Sweeper with Sling-Sat (4S) mission, Missel provided a path optimization strategy for ADR. In [10], Yu considered the problem of servicing multiple debris in a GEO orbit with one SSc. The goal is to find the best sequence of targets with the minimum Δv cost. Most of these studies focused on fuel cost. In addition to the fuel, time is another criterion that should be taken into consideration. Out of all possible ways to perform ADR, the best trajectories are those that minimize the fuel cost and the duration of the travel. Taking biobjective into account, Madakat [11] studied the problem of removing a list of space debris, and proposed an exact algorithm based on a branch and bound procedure to compute the set of nondominated (fuel cost, duration) vectors. However, he did not consider ADR scenarios with multiple SScs. In this paper we consider the problem of removing multiple GEO debris with multiple SScs. The goal is to find a set of optimal planning schemes with minimum fuel cost and travel duration.

Recently, hybrid optimal control (HOC) theory has been applied to the solution of space mission planning. HOC problems are those problems that include both continuous-valued variables and categorical variables in the problem formulation [12]. In [13], Ross et al. introduce an HOC method to tackle the increasing sophistication of space missions, and proposed a formalism that can free mission planners to focus on high-level decision making by automating and optimizing the details of the inner loops. Conway [12], Chilan [14,15], Englander [16] and Wall et al. [17] all applied the HOC method to solving certain space mission planning problems, including asteroids-visit problem and autonomous interplanetary mission. In [10], Yu et al. applied HOC theory to solving GEO debris removal problem.

In this paper we consider the scheduling of the ADR mission as a HOC problem, and use hybrid automaton to model and address it. This paper is organized as follows. Section 2 analyzes the process of the debris removing in detail and describes the mission scenario researched in this paper. Section 3 presents the model of the HOC problem, and details the steps of categorical state space modeling, continuous-time dynamics modeling, continuous-valued state and control spaces modeling, transition/switch events modeling, automata encoding and cost functions modeling. Section 4 gives the solution method for the problem. And in Section 5, numerous examples are carried out to demonstrate the effectiveness of the model and solution method. Single-SSc and multiple-SSc scenarios are also compared and discussed in this section.

2. Mission scenario

NASA, ESA, and other relevant authorities have begun to respond to the orbital debris problem by placing requirements [18] and issuing new projects for debris mitigation upon new space systems [19,20]. Numerous independent robotic concepts, ranging from classical space-based garbage scows to momentum and electrodynamic tethers, drag augmentation devices, solar and magnetic sails, and other exotic techniques, have all been considered [8,21]. In this study, we only consider ADR using a tether system.

Taking ROGER as an example [20], in the process of debris removal (see Fig. 1), the mission scenario begins with the launch of the ROGER servicing satellite into a geostationary orbit. And then phase to an orbit position, where the rendezvous maneuver to the first target satellite can start. After a series of rendezvous proximity operations (RPO), the ROGER will be pointed to the center of the target and the capture mechanism will be released. After the capturing and stabilization maneuvers, ROGER will inject the debris into the graveyard orbit, where a separation will be performed. Finally ROGER starts the next phase of RPO, and repeats the removing actions until all of the debris are removed.

Ignoring the first phase of launching, the debris removal process contains: RPO, capture operations and release operations. Capture and release operations are serial activities that out of our consideration. Therefore, the emphasis of the mission planning is put on finding the best mission assignment scheme, the best mission sequence for each SSc and the optimal RPO trajectories. RPO is an appealing and challenging area of study and much work has been done to address it. In order to simplify the problem, we take two-impulse phasing maneuver to perform RPO. In addition, we assume that once the SSc passed the graveyard orbit, it can release the debris immediately. Meanwhile, it is defined that the SSc originally stays on a maintenance station in GEO belt. When the whole mission is completed (all targets of the SSc are removed), the SSc should finally return to its original location as it is required to have certain routine maintenance (e.g. refueling, fixing).

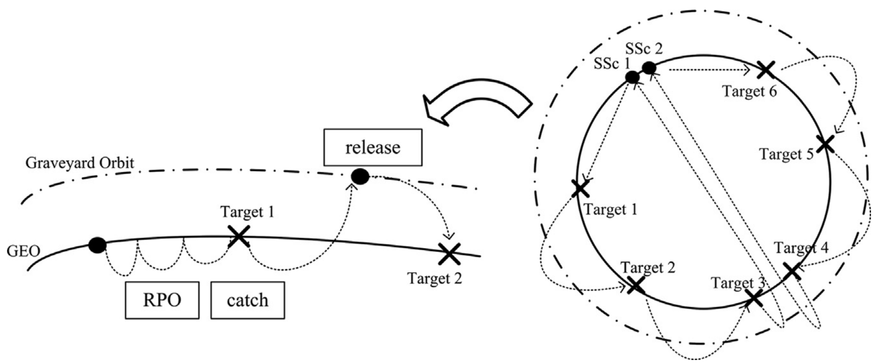

Fig. 1. Mission scenario.