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Biobjective planning of an active debris removal mission ☆

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ABSTRACT

The growth of the orbital debris population has been a concern to the international space community for several years. Recent studies have shown that the debris environment in Low Earth Orbit (LEO, defined as the region up to 2000 km altitude) has reached a point where the debris population will continue to increase even if all future launches are suspended. As the orbits of these objects often overlap the trajectories of satellites, debris create a potential collision risk. However, several studies show that about 5 objects per year should be removed in order to keep the future LEO environment stable. In this article, we propose a biobjective time dependent traveling salesman problem (BiTDTSP) model for the problem of optimally removing debris and use a branch and bound approach to deal with it.

1. Introduction

The number of space objects with diameter above 10 cm is estimated, nowadays, at about 12,000. Only 10% of these objects are operational and the others constitute space debris. The number of space debris will continue to increase even if future launches are suspended making the collision with an operational satellite more probable [7]. Since consequences of collisions with debris may prove dramatic, avoidance maneuvers or missions to remove debris are necessary [4]. As removing all space debris would be quite expensive, the idea is to determine the debris which are more likely to cause collisions and remove them first. According to [8–10], it would require removing about five objects per year, to keep the future Low Earth Orbit (LEO) environment stable.

To remove space debris, a possible solution is to design a moving space vehicle that captures LEO space objects into nets and drags them down safely from the space lanes. In addition to the cost, time is another criterion that should be taken into consideration. Most collisions are not debris/satellite but rather debris/debris and result in an increasing number of space debris. So the earlier the removal is finished, the less new debris are generated. Once some critical debris have been identified, the Active Debris Removal (ADR) should move from its own orbit and visit each debris once until all have been dealt with and then return to its initial orbit. Out of all possible ways to perform such a trajectory, the best trajectories are those that minimize the cost and the duration of the travel.

Wadsley and Melton [18] investigated the problem of visiting a set of satellites for servicing. In their approach, the only criterion to be optimized is the cost and they made different simplifying assumptions. The interorbital transfer durations are assumed to be constant and equal. The satellites orbits are considered as circular and the semi-major axes of all the satellites in each case are assumed to be equal. These assumptions define a time dependent traveling salesman problem (TDTSP). An instance of 20 satellites has been solved showing the optimal service order which minimizes the mission cost using a dynamic programming algorithm. Stodgell and Spencer [16] investigate a similar satellite rendezvous problem minimizing the total cost and the total time criteria. This problem is modeled as a

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biobjective traveling salesman problem (BiTSP). The orbits are supposed to be elliptical. Between each pair of debris, the costs corresponding to different transfer possibilities are computed and only the transfer minimizing the travel cost is retained. They have been able to solve a six target version, giving the set of non-dominated vectors using a multi-objective genetic algorithm (GA). GA is a search heuristic that mimics the process of natural evolution. As all meta-heuristics, GA does not guarantee the quality of the returned solutions. Murakami and Hokamoto [12] present a Lambert-based strategy in order to deorbit three LEO debris with a strong duration constraint.

In this article, we study the problem of removing a list of space debris. We propose an exact algorithm based on a branch and bound procedure to compute the set of non-dominated (cost, duration) vectors and give for each of these vectors a feasible solution.

In order to study different transfer possibilities, we do not assume the transfer time between debris orbits to be constant. Thus, between each pair of orbits, one has several transfer possibilities which depend on the arrival time to the departure orbit. This classifies the problem as a biobjective time dependent traveling salesman problem (BiTDTSP). BiTDTSP is clearly NP-hard as a generalization of the standard TSP. The paper is organized as follows. In the next section, we describe the problem of removing space debris. Section 3 is devoted to the presentation of our branch and bound procedure. Results are reported in Section 4 and conclusions are provided in the last section.

2. Problem description

2.1. Context

Given n debris to be removed, ADR has to move from its own orbit and visit the n debris in order to collect them. Thus, the ADR has to achieve n space rendezvous to meet each debris on its orbit. The quantity of fuel burned during each transfer from an orbit i to an orbit j, denoted by c_{ij}, represents the transfer cost. The duration of the transfer is denoted by t_{ij}. The quantity of fuel burned during the mission should not exceed the ADR capacity, thus the cost cannot exceed a fixed cost c_{max}. Moreover, the mission must end before a fixed date t_{max}. Costs and durations depend on the way the rendezvous is achieved. Several space rendezvous techniques are possible.

2.2. Definition of a space rendezvous

2.2.1. Principle

A space rendezvous between a debris and ADR is an orbital maneuver where both arrive at the same orbit and approach to a very close distance. There are several ways to perform a space rendezvous as shown in [13,11,1]. In this article, one only considers standard methods to design a space rendezvous with a valuable tradeoff between optimality of the proposed transfer and computation time. For each debris i, t_i denotes the time at which the ADR reaches debris i. Once the ADR has reached debris i, it can immediately start the next transfer to reach debris j or wait before beginning the transfer. $A_{ij}(t_i)$ denotes the set of feasible transfers between the orbit of debris i and the orbit of another debris j given t_i. In the following, we describe the standard orbital maneuver based on the two impulsive velocity changes used in this article.

2.2.2. Elliptical transfer

Given a specific starting point and an arrival point, the ADR moves between the two orbits by performing exactly two pulses. Lambert was interested in the problem of determining the transfer orbit given a starting position and velocity, an arrival position and velocity, and a transfer duration [14].

Lambert's theorem states that given two points, Sin orbit i and Ein orbit j, and given a period T of transfer, there is exactly one arc of a conic linking $S$to Esuch that the duration for traversing the arc is equal to T [14]. A universal Lambert algorithm was developed in [17]. A more detailed description of this algorithm can be found in [15]. In order to consider several interorbital transfer possibilities, we use in this article the elliptical method to perform any space rendezvous. The cost of the transfer is represented by the quantity of fuel burned to achieve this transfer. This quantity is related to the change in speed. To achieve each transfer, the ADR undergoes exactly two pulses as shown in Fig. 1. The cost of the transfer from an orbit i to another orbit j depends on the departure time from i and the arrival time to j. Thus, every pair of possible departure and arrival times leads to a new transfer cost c_{ij}. The duration of the transfer is the sum of the waiting time in the departure orbit and the travel time to the arrival orbit. The cardinality of the set $A_{ij}(t_i)$ may be very high depending on the number of possible departure positions and the number of possible durations.

2.3. Formulation of the problem

In the following, we assume that each elementary transfer requires a minimum cost δc_{min} and a minimum duration δt_{trans}. We assume as well that the service time on each orbit takes a duration of $t_{serv} = 10$ days. The mission costs at most c_{max}, which corresponds to the ADR fuel capacity, and cannot exceed a fixed duration t_{max}.

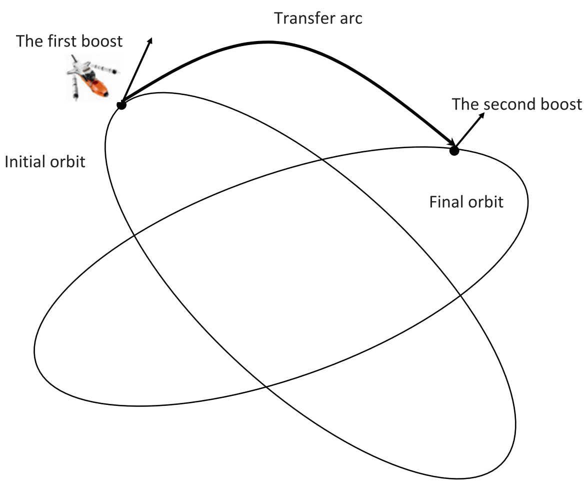

Fig. 1. The transfer orbit of the ADR using the elliptical maneuver.