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Executive Summary of the Thesis

Debris sequence optimization for an Active Debris Removal mission using a multi-indices rating system based algorithm

Laurea Magistrale in Space Engineering - Ingegneria Spaziale

Author: Alex Yousef Al Naber
Advisor: Prof. Camilla Colombo
Co-advisor: Giacomo Borelli
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1. Introduction

Nowadays, more and more companies are launching satellites into space, taking to an overpopulation of the Earth's orbits of interest, such as Low Earth Orbits (LEO) and Geosynchronous Earth Orbits (GEO). Since the first version of the Space Debris Mitigation Guidelines document in 2002, the Inter-Agency Space Debris Cordination Committee (IADC) settled some guidelines for the post-mission disposal (PMD) in order to prevent the debris excessive growth. For a debris in LEO, it should be transferred into a disposal with an expected residual orbital lifetime of 25 years or shorter (although a direct re-entry is preferable). However, it will be necessary not only to implement all the end-of-life regulations of the satellite, but also to actively act to free the most used orbits from the objects with the greatest impact in terms of potential risk. Liou [4] analyzed different scenarios considering both the case with no mitigation at all, the case with PMD only and the case with ADR with different removed objects per year. Plotting the debris growth trend in the 3 cases showed that only by combining PMD with an Active Debris Removal (ADR) mission with 5 deorbited debris per year a satisfactory result can be obtained.

The aim of this thesis is to implement a mission designer for a multiple-target ADR mission that will find the best route in order to remove the required number of debris. The algorithm will take account not only of the Δv necessary for each travel, but also of many characteristics of the debris that influence the capture feasibility and its impact on the orbital environment. To do that, they will be used some specific indices, the *operability index* I_{OP} and the *environmental index* I_{ENV}.

2. Mission architectures

In order to fulfill the goal of this dissertation, different strategies can be adopted. Each equally effective, and each with its pros and cons. A summary flowchart is showed in Figure 1.

2.1. RAAN change strategy

Among the various orbital transfer maneuvers, those out-of-plane are certainly the most expensive. As for the change of inclination, the cheapest possibility is to provide an impulse perpendicular to the plane at the apogee. As for the Right Ascension of the Ascending Node (RAAN) change, there are two ways to compensate for the

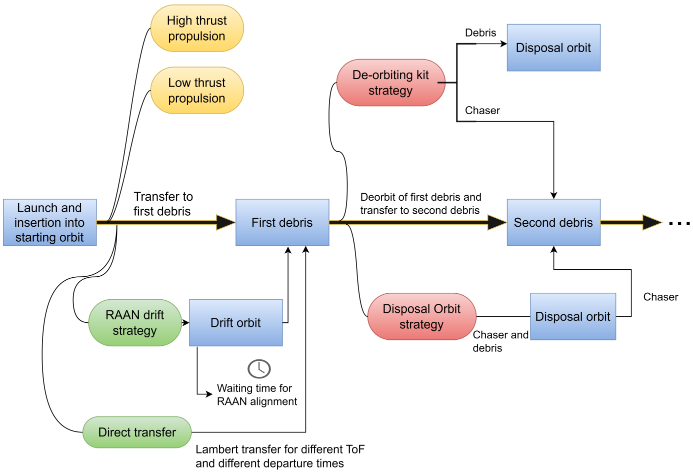

Figure 1: ADR mission deorbiting phases flowchart considering different architectures

difference between the departure orbit and the arrival orbit.
The simplest way is the direct change through an out-of-plane impulse. This manoeuvre, unlike the other strategy, results in a transfer with small ToF. However, it is very expensive and it could preclude lots of transfers with a large RAAN difference.
An alternative strategy takes advantage of the RAAN variation due to the Earth's oblateness effects, particularly to the second zonal harmonic J_2. To reduce a large RAAN difference between initial and final orbit, the transfer can be performed using an intermediate *drift orbit*, with specific semi-major axis and inclination.

2.2. De-orbit strategy

In order to be safely deorbited, the debris has to be taken into a de-orbiting orbit. There are mainly two strategies by which the chaser can deorbit the debris. The first one is the Deorbiting Kit Strategy (DKS). This strategy consists in attaching to the debris a deorbiting kit, like a thruster, that will take the debris into the disposal orbit. The other one is the Disposal Orbit Strategy (DOS). In this case, the chaser attaches itself directly to the debris and takes to the disposal orbit.

2.3. Propulsion type

The different choice of thrusters and propellant will influence the dynamics of orbital transfers, the propellant consumption, the transfer duration and computational cost.
High-thrust propulsion is the one that we have in chemical propulsion systems. The manoeuvres carried out by a chemical thruster can be considered to be impulsive. Impulsive manoeuvres are such that can be modelled as instantaneous change of magnitude and direction of the orbital velocity vector.
Low-thrust propulsion is, instead, the one that we have in electric propulsion system. In this case, the manoeuvres will no longer be impulsive, and that means that the spacecraft will change position during the manoeuvres, and it will typically perform several revolutions before reaching the desired orbit. Moreover, during the manoeuvres it will be also necessary to take account of the variation of orbital parameter due to the low-thrust perturbing acceleration and of the secular effects due to J_2.

2.4. Selected mission architecture

In this dissertation, the mission architecture for active debris removal of multiple target selected is the DKS, adopting a direct RAAN change and considering high thrust propulsion.

3. Time-Dependent Travelling Salesman Problem

One of the main challenges related to ADR missions is finding the best sequence of debris to be deorbited within the same mission, optimising a specific cost function (i.e., delta-v, time-of-flight, mass deorbited). This can be reduced to a discrete sequence/path optimisation problem similar to the Traveling Salesman Problem (TSP), widely known in literature. As suggested by the name, TSP is based on the problem regarding the best path that a salesman should do to visit a certain number of cities using as little fuel as possible, starting from his current city. A generic scheme for the TSP is showed in Figure 2. However, the classic TSP shows some differences with the ADR sequence optimization problem. Firstly, the debris in-orbit represent the cities of the TSP, which have to be connected by an optimal path. However, unlike cities in the TSP, space debris change their position with time, and then the transfer cost between them will depend on their actual position and then on the time. This more general case of TSP is known as Time-Dependent Travelling Salesman Problem (TDTSP), and it is in gen-

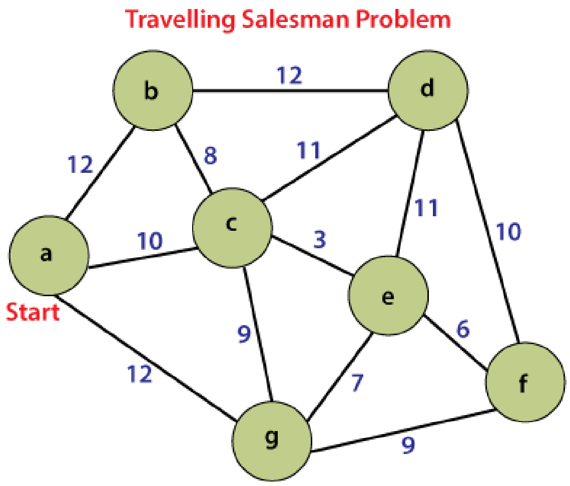

Figure 2: Example of a generic TSP scheme. (from [1])

eral more complex since it is necessary to take into account the displacement of the nodes over time.

4. Cost function indices

In this dissertation, the quality of a solution is calculated with the help of a fitness function that has to be minimized. This function will take into account not only the Δv required for transfers between debris, but will also take into account the two indices, already defined in Borelli's paper [3].

4.1. Environmental Index

The environmental index I_{ENV} describe the criticality of an inactive object to the debris environment. This index therefore expresses how convenient it would be to remove a certain debris to reduce the risk of collisions in that orbital region. The environmental index used was defined in [2] and used in Borelli et al. [3]:

$$I_{ENV} = \left(\frac{\Phi}{\Phi_0}\right) \cdot \left(\frac{M}{M_0}\right)^{1.75} \cdot \left(\frac{life}{life_0}\right) \quad (1)$$

where Φ is the flux of debris, M the debris mass and $life$ is the orbital lifetime function. The higher its value, the more convenient it will be to deorbit a certain debris given its high risk of collision. I_{ENV} is then normalised with the value corresponding to an object of 1000 kg of mass in an orbit of 800 km of altitude and 98.5° of inclination.

4.2. Operability Index

This index quantifies the difficulties in approaching and capturing the debris. For the purposes of this thesis a rigid contact capture technique has been considered, for example through one or more robotic arms. The operability index takes into account three factors that will have a big influence on proximity operations:

- Attitude state
- Mass
- Illumination conditions

The *attitude state* represents the rotational state of the debris, and in order to rigidly attach the debris, the chaser has to synchronize to its motion. *Mass* represents another major constraint since greater mass leads to greater catching difficulty. Finally, the *illumination conditions* are very important for proximity operations. In fact, the chaser will mainly make use of sensors to precisely locate the satellite and to derive its precise shape and true attitude state. In order for these sensors to work, they need the target to be illuminated by the sun. The operational index is therefore defined as follows:

$$I_{OP} = P_{ill}\left(\frac{a_{s0}(L,\omega_f)}{a_s(L,\omega_f})\right)\left(\frac{M_0 - M}{M_0}\right) \quad (2)$$

where P_{ill} is the percentage of the orbit with favorable lighting conditions, $a_s(L,\omega_f)$ is the estimated acceleration to obtain a full synchronisation, ω_f is the angular velocity derived from the apparent angular velocity and M is the mass of the debris. The higher its value, the easier it will be to capture and deorbit a certain debris. I_{OP} is then normalised with the value of a debris with $M = 1000\ kg$, $\omega = 3°/s$ and $L = 2\ m$.

5. Branch&Bound algorithm

The algorithm developed in this dissertation is based on Branch&Bound algorithm concept. In fact, the search for an optimal solution will use a fitness function to quantify the quality of the solution and whether to proceed in that direction for the search, or to truncate that branch instead. the fitness function used for the algorithm will not only take into account the transfer cost required to reach the next detritus, but through the use of the two indices, I_{OP} and I_{ENV}, it will also take into account respectively how convenient it is to deorbit a certain debris based on the difficulty of capturing it and the benefit of deorbit it. The cost function will then consist of a weighted sum of these three elements. Since the goal of the algorithm will be to minimize it, the inverses of the two indices will be considered in the function. The cost function at each iteration will thus be computed as follows:

$$f_{COST} = \alpha_1 \cdot \frac{\Delta V}{\Delta V_0} + \alpha_2 \cdot \frac{I_{ENV}}{I_{ENV,0}} + \alpha_3 \cdot \frac{I_{OP}}{I_{OP,0}} \tag{3}$$

where α_1, α_2 and α_3 are the weights assigned respectively to the transfer cost ΔV, to the Environmental Index I_{ENV} and to the Operational Index I_{OP}. The three weights can be tuned according to mission requirements. The three components of the weighted sum are also normalized so that their values are between 0 and 1 and thus comparable.
The indices of the entire debris population can be pre-calculated according to 1 and 2 and organized into a matrix since they depend solely on debris characteristics. As for Δv, it will be calculated from time to time depending on the orbital parameters of the departure and arrival debris at the time of departure. For each travel, the transfer cost Δv is computed using the function *lambertMR.m*. This function solve the Lambert's problem given the initial and final position and velocity vectors and the desired time of flight, giving as outputs the initial and final velocity vectors of the Lambert transfer. In order to consider more cases that can lead to more optimal solutions, this operation is repeated for five different departure times equally spaced. Moreover, the transfer cost is computed for different time of flight (ToF). The ToF vector is obtained by dividing the revolution time of the arrival orbit equally and considering only the times from the fourth element onward, since times that are too low would lead to solutions that are impossible or at any rate certainly too expensive. In order to avoid sequences that are infeasible or otherwise too costly from a transfer cost perspective, transfers that have $\Delta v > 1800\ m/s$ are discarded at each iteration. Due to orbital perturbations, the mean anomaly will not be the only parameter to vary. In this dissertation, the J_2 perturbations due to Earth oblateness are considered. In this simplified perturbation model, the only parameters that vary are the Right Ascension of the Ascending Node (RAAN) Ω, the Argument of Perigee (AoP) ω and the mean anomaly M. Their values will change over time in that way:

$$\frac{d\Omega}{dt} = -\frac{3}{2}\left(\frac{r_E}{p}\right)^2 nJ_2 \cos i \tag{4}$$

$$\frac{d\omega}{dt} = \frac{3}{4}\left(\frac{r_E}{p}\right)^2 nJ_2(5\cos^2 i - 1) \tag{5}$$

$$\frac{dM}{dt} = n + \frac{3}{4}\left(\frac{r_E}{p}\right)^2 nJ_2\sqrt{1-e^2}(3\cos^2 i - 1) \tag{6}$$

where r_E is the Earth's radius, i is the inclination, e is the eccentricity and n and p are respectively the mean velocity and the semilatus rectum, and they are computed as:

$$n = \sqrt{\frac{\mu_E}{a^3}} \tag{7}$$

$$p = a(1-e^2) \tag{8}$$

where μ_E is the Earth's gravitational constant and a is the semi-major axis. Then, it is necessary to consider their variation both during the waiting time between the different departures time and during the ToF considered in Lambert's problem.
At the end of one cycle of the iteration there will be a matrix where for each debris, each ToF and each start time the weighted sum calculated as in Equation 3 will be reported. After sorting them, it considers only a percentage of the best transfers (determined by the user) while discarding all others. This will avoid having to consider too many combinations in subsequent iterations, leading the algorithm to have prohibitive computation times. This step is based on the assumption that good single transfers will probably lead to an optimal overall solution.

6. Results

Different test cases are evaluated with the algorithm, which differ in the weight assigned to the three contributions of the cost function in Equation 3. In order to test the behavior of the algorithm, the first test cases (1,2 and 3) are scenarios in which the aim is to optimize only one parameter at a time. Test case 4 goes to simulate a mission scenario where you want to consider all three contributions in a balanced way, setting $\alpha_1 = 1$, $\alpha_2 = 0.6$ and $\alpha_3 = 0.6$. An additional test case considered (test case 5) is a scenario in which a decision is made to give much higher priority to indices than to transfer cost. To do this, the weights were assigned the value $\alpha_1 = 0.3$, $\alpha_2 = 1.5$ and $\alpha_3 = 1.5$. As a final test case (test case 6), it was thought to equally consider only the two indices and instead ignore the Δv term in the weighted sum.

In order to show how the algorithm performed in this several test cases, it was planned to plot for each of them the total value of each contribution of the weighted sum normalized to the maximum value. It will then be expected that the algorithm will go to minimize the contributions that have the most weight. In the bar graph in Figure 3 it can be seen that this prediction is basically right. In fact, in the first three test cases the minimized value is that of the only parameter considered. Then, in test case 4 it can be seen how the situation is more balanced even though Δv is the most minimized value and in fact the one with the highest weight. Increasing the weight of the indices, in test case 5 it can be seen how the value of Δv increases while that for the environmental index decreases. Then considering only the two indices, in test case 6 we can see how Δv increases further while $1/I_{ENV}$ continues to decrease. The fact that the two indices do not decrease in the same way as their weights increase is due to the lack of variety in the data due to the small population size and the many values assumed. In Tables 1 and 2 are listed the first ten sequence chosen by the algorithm for test case 1 and 5, in which it can be seen the difference in total transfer cost depending on whether only Δv is considered or whether indices are also considered. In this regard, it is good to remember that higher index values correspond to better solutions. In fact, in test case 5 it can be seen that the total value of I_{ENV} is much higher than in test case 1. As for I_{OP}, although it is not higher for all sequences, it always remains very high in contrast to test case 1, where a decrease is seen in the last sequence.

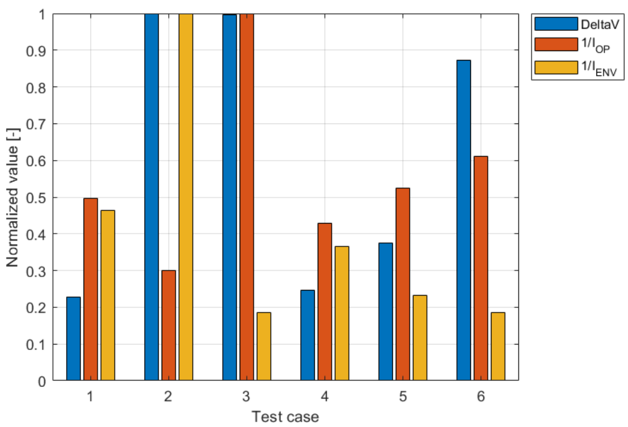

Figure 3: Bar graph of the normalized sum of the three contributions to the weighted sum Δv, $1/I_{OP}$, and $1/I_{ENV}$ that defines the functions cost that have to be minimized by the algorithm

Sequence	Total Δv [m/s]	Total I_{OP} [-]	Total I_{ENV} [-]
[57,47,55]	642	18.2251	3.7893
[57,47,56]	666	18.2630	3.7893
[57,45,38]	708	18.5105	2.8775
[57,47,49]	718	18.2460	3.7893
[57,45,55]	720	18.2876	3.7893
[57,47,54]	777	18.2755	3.7893
[57,45,49]	780	18.3085	3.7893
[57,47,66]	795	18.2441	3.7893
[57,47,38]	860	18.4480	2.8775
[9,22,28]	860	7.5471	0.6753

Table 1: First 10 sequences chosen by the algorithm for test case 1

Sequence	Total Δv [m/s]	Total I_{OP} [-]	Total I_{ENV} [-]
[71,67,57]	1587	12.6870	7.4106
[71,67,46]	1673	12.7958	7.4106
[71,67,47]	1693	12.7392	7.4106
[57,47,55]	642	18.2251	3.7893
[71,67,58]	1710	12.6784	7.4106
[57,47,56]	666	18.2630	3.7893
[71,67,45]	1762	12.8017	7.4106
[57,47,49]	718	18.2460	3.7893
[57,45,55]	720	18.2876	3.7893
[71,63,45]	1812	12.8173	7.4106

Table 2: First 10 sequences chosen by the algorithm for test case 5

7. Conclusions

In this thesis, an algorithm was developed for choosing the sequence of debris to be deorbit in a multi ADR mission. Compared to previously developed methods, which went for an optimization considering only the Δv or at most a bi-objective optimization considering time and Δv, in this dissertation it was aimed to enrich the research with the implementation of two indices, namely the *operational index* I_{OP} and the *environmental index* I_{ENV}. While Masserini's work [5] focused more on comparing two mission architectures (chaser and deorbiting kits) and the performance of different optimization algorithms based solely on the transfer cost, here more emphasis was placed on defining a cost function that would go into multiple aspects. The advantage of a multi-index cost function is to be able to maximize the benefits obtained from an ADR mission by deorbiting the debris with the greatest impact on the orbital belt, and to minimize the risks due to the high difficulty of capturing some debris, all while finding a good trade-off with the amount of propellant required. Although the algorithm makes use of several assumptions and simplifications, it still seems to lead to satisfactory results. In fact, always keeping the total Δv fairly limited, it succeeds in finding sequences whose debris has characteristics such that it has a higher risk of collision but still does not present too high a difficulty of capture, risking leading to failure of the entire mission due to irreversible damage to the chaser. Despite this assumption, the focus of this thesis was the algorithm behaviour in objects selections for ADR mission according to multiple ranking indices. Therefore, the modelling and analysis of the relative behaviour of the multiple indices was more of interest.

This dissertation can be more of a starting point for future developments. In fact, many simplifications are considered throughout the thesis. Firstly, different mission architectures can be studied. The analyzed architecture is on the whole quite simple: high thrust propulsion, direct RAAN change, and deorbiting kit strategy were chosen.

From the algorithm point of view, some improvements can be foreseen. The chosen method, inspired by Branch&Bound, is efficient for medium-sized problems. However, in more complex scenarios where the population of debris is significantly larger it an evolutionary algorithm may be more suitable. In addition, having adopted the RAAN direct change strategy and high-thrust propulsion, it was not deemed necessary to consider the total mission time among the parameters of the cost function since all the solutions found had very short total times. However, a future implementation could be to extend the cost function formulation to consider also the total time of the ADR mission, often an important parameter for mission planning and design.

In essence, many implementations can and should be made especially for its application in a real mission scenario. What this dissertation aimed at was to demonstrate how it was possible to use an index-based satellite rating system in selecting an optimal sequence of debris to orbit. Thus, the use of other types of indices, as discussed in the paper of Borelli et al. [3], or alternative indices should not be ruled out.

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