OPTIMAL RENDEZ-VOUS SEQUENCE FOR LEO DEBRIS CAPTURE

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Abstract: *The purpose of this study is to exploit the effect of Earth's non-sphericity perturbation, particularly due to the J_2 term, in order to optimize the capture sequence of potential orbital debris. In LEO, such cause of disturbance is prevailing over the others, and it acts by affecting the longitude of the ascending node (Ω), the argument of perigee (ω) and, accordingly, the true anomaly (ν). The goal of optimizing the ΔV is achieved by taking advantage of the rate of variation of Ω and ω, and compensating for the ΔΩ and Δω, present between the orbital transfer vehicle (chaser) and the debris to be captured (target). Obviously, the perturbation will lead to favourable variations of the orbital parameters only for some combinations of Ω and ω. Yet the presence of a debris population with random distribution of Ω and ω, makes this application particularly suited to the problem. The single maneuver has been modeled with a 4-impulse time fixed rendez-vous and the optimization problem has been addressed by implementing a hybrid evolutionary algorithm, which adopts, in parallel, three different strategies, namely, Genetic Algorithm, Differential Evolution and Particle Swarm Optimization.*

Keywords: *Trajectory optimization, Hybrid evolutionary algorithms, Debris removal, Multi-target rendez-vous, J_2 perturbation assist.*

1. Introduction

The steady increase of the number of debris in LEO, is matter of great interest and concern in the scientific community [1], as the problem calls into question the future of the exploitation of circum-terrestrial space. By this time, it is evident that putting into orbit new artificial satellites without worrying about their disposal and de-orbiting at the end of their operational life cycle is no longer a viable approach. On the other hand, intervening only on the "end of life" strategy of new satellites to be launched may not be enough. The amount of objects in orbit is such that the number of collisions and the resulting trail of debris that these produce, is likely to trigger a chain process difficult to predict. Internal research of top agencies and companies [2] are addressed toward the design of missions with active debris removal goals. Top-level timeline includes the following cyclic operations:

- Target debris rendez-vous
- Close approach operations
- Non-cooperative de-tumbling and docking
- De-orbiting
- New target debris rendez-vous

To ensure each phase of the mission is completed successfully, it is necessary that research moves important steps towards different subject areas. In fact, to maximize the number of targets a certain orbital transfer vehicle (chaser) is able to reach, specific algorithms for optimizing the ΔV between the orbits of arrival and departure are essential, as well as optimizing the debris sequence. During the approach and de-tumbling phase, 3D vision algorithms shall allow an accurate 3D reconstruction of target inertial properties and dynamics. Finally, non-cooperative docking will require a completely autonomous and reliable relative navigation system.

The present study arises from these needs and focus efforts on the rendez-vous sequence of non-cooperative objects. The orbital slot of greatest interest is that in LEO, containing debris of larger dimensions, such as upper stages and inactive satellites, with masses exceeding one ton. Since the problem is most critical in that orbital slot, an assessment of the perturbations in this area was first conducted. The J_2 perturbation due to Earth's non-sphericity is predominant, thus it is possible to use it in order to optimize the ΔV required for transfers between a target and the other. Such disturbances intervene only on the longitude of ascending node (Ω), argument of perigee (ω) and, accordingly, the true anomaly (ν). With the availability of a wide target population, the rendez-vous sequence will be fixed so that the rate of change of orbital parameters affected by the J_2 effect tends to align them with the chaser's. Hence it is possible to save the ΔV needed to compensate for $\Delta\Omega$ and $\Delta\omega$ between target and chaser. For the calculation of ΔV associated with each sequence step, a 4-impulse time fixed rendez-vous maneuver has been modelled, and the optimization parameters have been evaluated by means of a hybrid evolutionary algorithm. The results obtained have been compared with those produced by the same algorithm, nullifying the contribution of the J_2 disturbance and highlighting the gain obtained in terms of ΔV.

Hand in hand with the active debris removal missions, the study of optimal rendez-vous strategies with multiple non-cooperative objects can be very useful for other purposes such as servicing and refuelling of inactive satellites, willing to prolong their operational life cycle.

2. Orbital debris hazard and mitigation strategies

The space activity, since its inception, has always given a relatively low value to disposal of satellites and orbiting objects, once the operational life cycle reaches the end. Only in recent decades necessity led to draw up precise guidelines with the aim of limiting the number of debris in Earth orbits (from LEO to GEO). Yet the risk inherent in the presence of an increasing number of objects in orbit, tends to worsen as much as emerging nations acquire the technology necessary for the exploitation of the circum-terrestrial space. Currently, the overall number of objects in LEO with characteristic dimensions above 10 cm is more than 10,000.

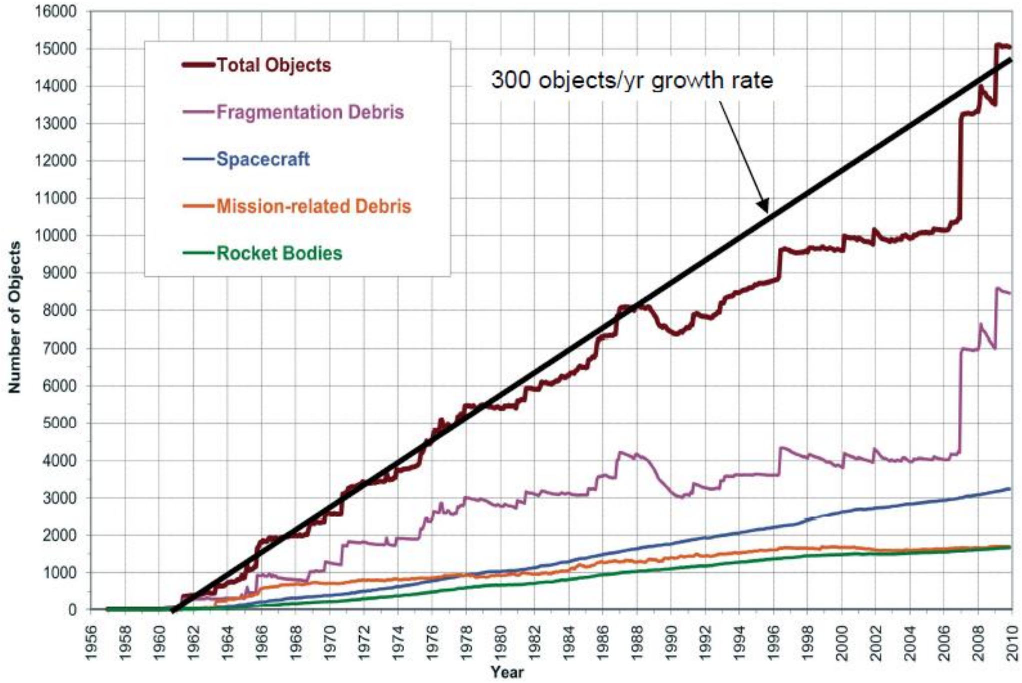

Figure 1: LEO and GEO orbiting objects [2]

Approximately one-sixth of the causes of fragmentation of objects orbiting the Earth are still unknown. However, most of them can be identified among:

- Deliberate actions
- Propulsive causes
- Batteries issues
- Collisions
- Aerodynamic drag

Although the cause of fragmentation by collision is nowadays still restrained, in the next century it is expected to be the leading and no longer controlled cause of generation of debris in LEO. Recent studies [3], show that even with no future launches of objects in orbit, collisions between those already present would lead to a continually growing number of debris.
The uncontrolled growth of debris in LEO may be limited only by reducing the number of collisions. To avoid a catastrophic collision chain there are only two modes:

- De-orbiting of orbital objects
- Disposal on alternative orbits

In the last decade, the international community decided to adopt rules specifically aimed at the Post Mission Disposal (PMD). These guidelines provide that any payload or upper stage should be removed from its operational orbit within 25 years following the end of his life. Yet considering the current orbital environment and the overall number of items already reached, even if all new satellites followed the PMD guidelines completely

(100%) this would not reduce the risk of a collision cascade. Hence the adoption of a plan of Active Debris Removal (ADR) is strongly suggested [4]. The following figure shows the trend forecasts performed with the LEGEND model, developed by NASA [5]:

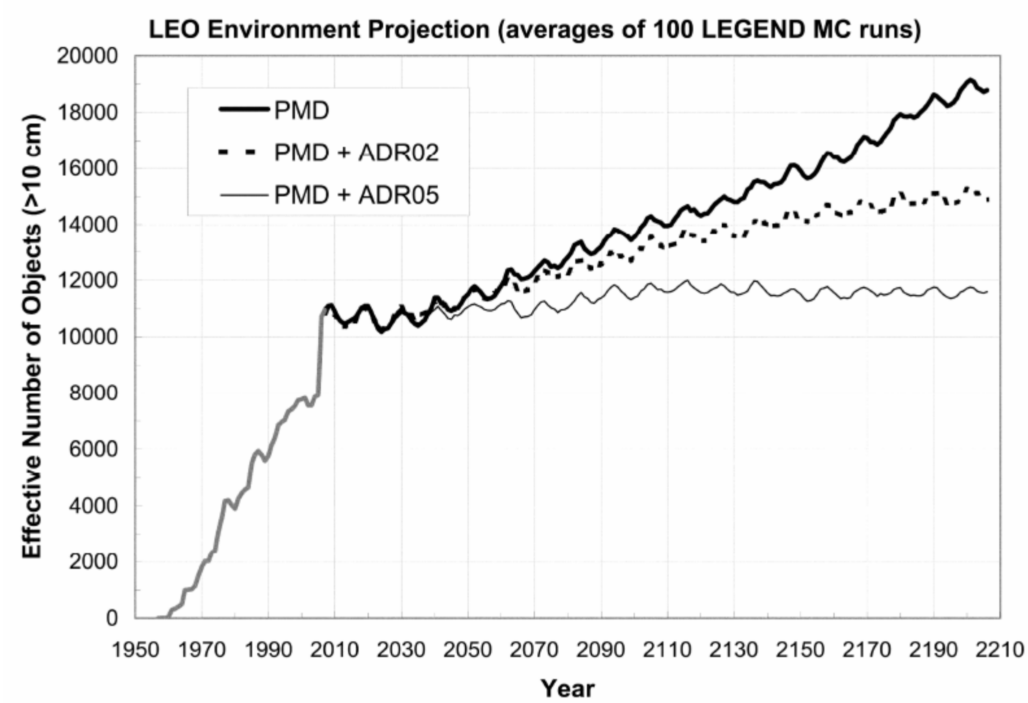

Figure 2: Orbiting objects growth trends [5]

The following three case studies have been taken into consideration:

- PMD at 90%
- PMD at 90% + 2 removed objects per year
- PMD at 90% + 5 removed objects per year

Of course, if it is not possible to reach 90% of PMD, it would be required a higher rate of ADR to be able to obtain a constant curve on the number of objects in orbit. Finally, by equipping future payload devices with Active Collision Avoidance (ACA), it is possible to act in synergy with the PMD and ADR and achieve the common goal of making the orbital environment less risky for future missions .

3. Single-target maneuver optimization

The ultimate goal is to minimize the ΔV associated with a sequence of rendez-vous maneuvers in LEO, not necessarily circular and/or coplanar, sometimes very close to each other. Each single rendez-vous has been modelled as a 4-impules time fixed maneuver, as shown in the following figure:

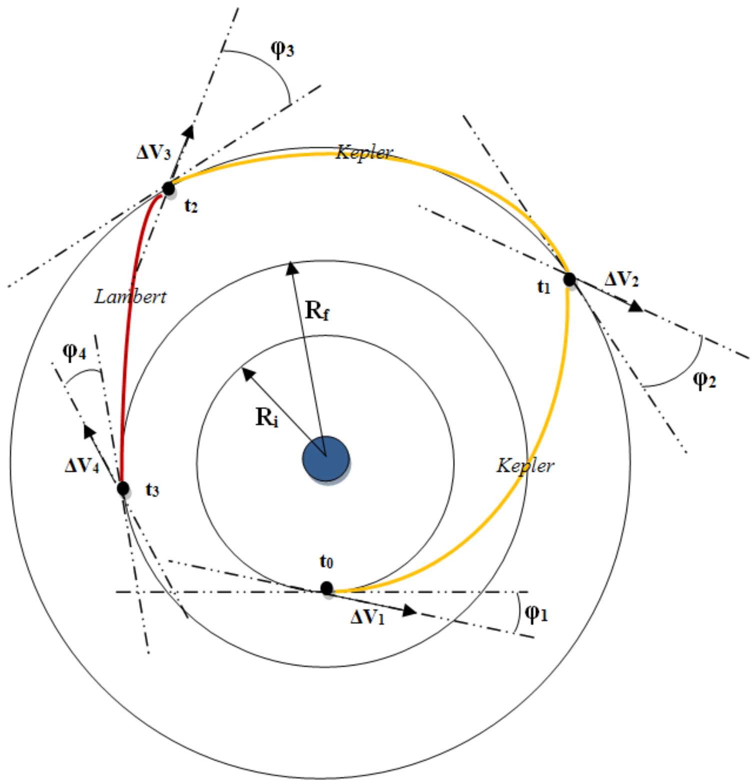

Figure 3: 4-impulse time fixed rendez-vous maneuver scheme

The entire maneuver can be split into 3 arcs and 4 impulses, defined by the variation of velocity vector and the angle of shot. t_0 is the maneuver start time, whereas t_3 is the instant at which rendez-vous occurs. The difference $T_{fi} = t_3 - t_0$ is the meneuver time of flight, defined as input to the optimization algorithm. R_i and R_f are the position vectors of the chaser and target on their orbits, respectively. Thus at the end of the maneuver, the chaser will transfer from R_i to R_f. The optimization program (Fortran-based language) used to find the optimal solution, which minimizes the ΔV associated with the rendez-vous, is a hybrid evolutionary algorithm (HEA) based on the cooperation among three different strategies: Genetic Algorithm (GA), Differential Evolution (DE), Particle Swarm Optimization (PSO). Recent studies [6], [7] confirmed that, for rendez-vous optimization problems, it may be convenient to adopt a hybridization strategy. In this case, balancing the strengths of the three EA in parallel, considerable advantages can be obtained, in terms of convergence speed and optimization efficiency. In fact, in the hybrid procedure, any algorithm acts on a different population, but the best individual solutions are allowed to migrate from one population to another. The migration takes place only at predefined intervals within the iterative sequence. Algorithms are all initialized with random populations of solutions and then, following the evaluation of the fitness function, the best solutions are exchanged and crossed between the different selection strategies. In order to successfully implement the HEA strategy to optimize a single 4-impulse time fixed rendez-vous, it is first necessary to define the useful components of the solution vector. These dimensionless components will uniquely characterize the maneuver. In the case considered the solution vector will be defined by:

$$\text{POPULATION} = [t_1 - t_0,\ t_3 - t_2,\ \Delta V_1,\ \Delta V_2,\ \varphi_1,\ \varphi_2]$$

Furthermore, the following dimensionless input vector shall be provided both for the chaser and the target:

$$\text{PO} = [a,\ e,\ \Omega + \omega,\ T_{in},\ i,\ \omega]$$

The following flow-chart summarizes the steps undertaken by the optimization program, leading to the overall ΔV calculation.

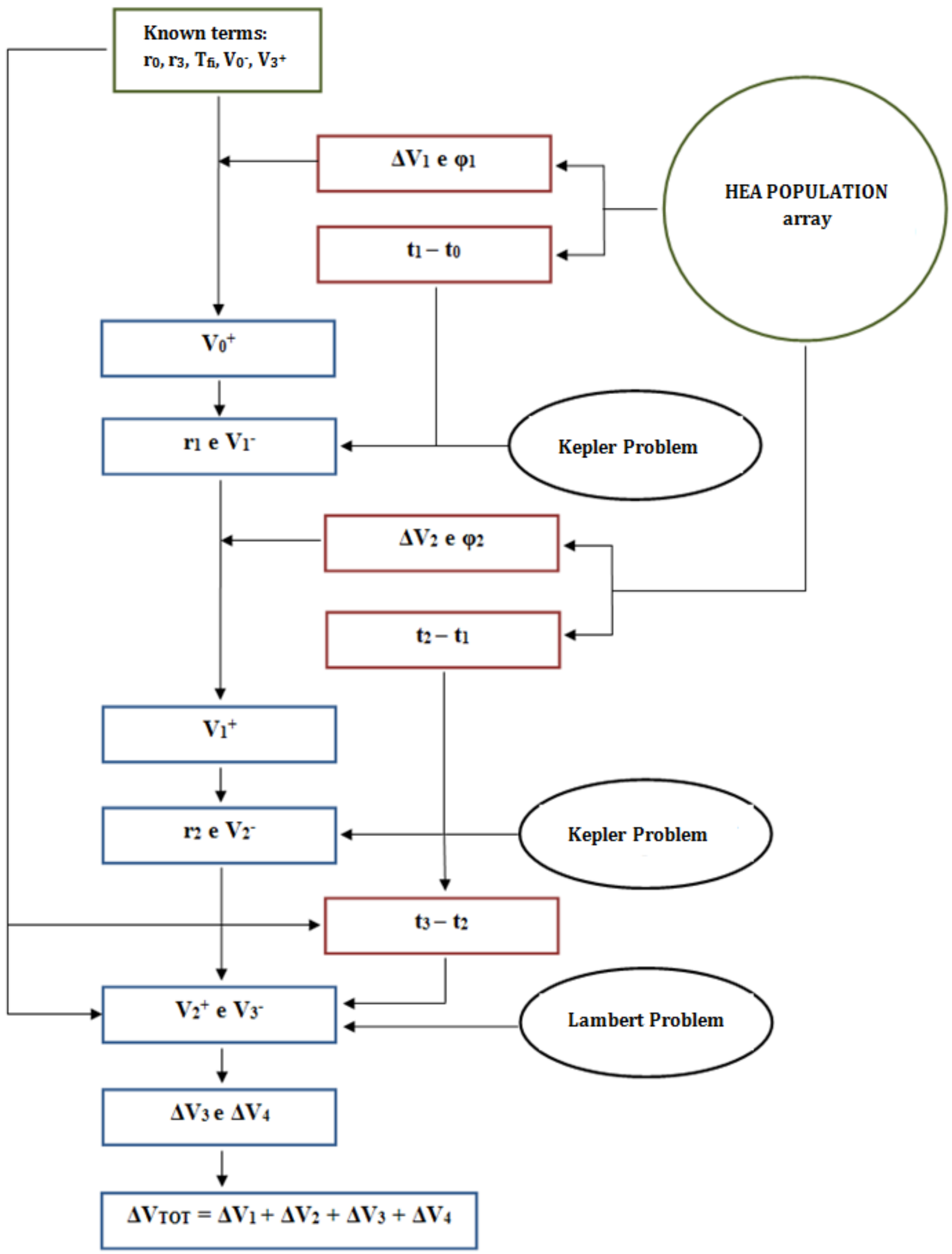

Figure 4: HEA optimizer flow-chart

The hybrid evolutionary algorithm assigns random values to the initial POPULATION array, thus ΔV_1, φ_1 and $t_1 - t_0$ are included in the first generation outputs. At this point, velocity components, immediately after the first burn, can be directly derived:

$$\overrightarrow{V_0^+} = \overrightarrow{V_0^-} + \overrightarrow{\Delta V_1}$$

Since V_0^- and $t_1 - t_0$ are known, a dedicated subroutine is used to solve the Kepler problem on the first arc. Outputs are expressed in the form of the velocity vector V_1^- and the position r_1 at time t_1. From the first generation of POPULATION array, ΔV_2, φ_2 and $t_2 - t_1$ are known. Therefore, velocity vector after the second burn is given by:

$$\overrightarrow{V_1^+} = \overrightarrow{V_1^-} + \overrightarrow{\Delta V_2}$$

Likewise another Kepler problem shall be solved, in order to compute the velocity vector V_2^- at the end of the second maneuver arc and at r_2 position. Since time of flight is known, it is now possible to derive the time associated with the last maneuver arc:

$$t_3 - t_2 = T_{fi} - (t_2 - t_1) - (t_1 - t_0) = T_{fi} - t_2 + t_0$$

Where t_0 is the maneuver start time. Finally, since initial and final position on the third maneuver arc are known by means of r_2 and r_3, Lambert problem is solved, producing as outputs the velocity vectors V_2^+ and V_3^- at orbital positions r_2 and r_3, respectively. It is now possible to compute the last two burns magnitudes:

$$\Delta V_3 = |V_2^+ - V_2^-|$$

$$\Delta V_4 = |V_3^+ - V_3^-|$$

Global ΔV associated with the 4-impulses time fixed rendez-vous maneuver is then obtained by summing up the single burns contributes:

$$\Delta V_{TOT} = \Delta V_1 + \Delta V_2 + \Delta V_3 + \Delta V_4$$

The HEA optimizer fitness function is directly linked to the ΔV_{TOT} parameter. In fact, solutions with lower ΔV_{TOT} will be given a higher score and be encouraged in the iterative evolutionary process. HEA's driving parameters can be summarized as follows:

Table 1. HEA set up parameters

Parameter	Description	HEA values
NTOT	Initialization solutions	490
TFI	Time of flight	V (variable)
PO	Input vectors	$[a,\ e,\ \Omega+\omega,\ T_{in},\ i,\ \omega]$
POPULATION	Solution vector	$[t_1-t_0,\ t_3-t_2,\ \Delta V_1,\ \Delta V_2,\ \varphi_1,\ \varphi_2]$
NP	POPULATION dimension	6 (1-target), 7 (N-target)
NG	Number of iterations	200
PARMIN	POPULATION min values	[0, 0, 0, 0, -3.5, -3.5, 2 (*)]
PARMAX	POPULATION max values	[V, V, 0.3, 0.3, 3.5, 3.5, N+1 (*)]
NIGE	GE initialization solutions	300 (61%)
NIDE	DE initialization solution	160 (33%)
NIPSO	PSO initialization solutions	30 (6%)

(*) in a 7D POPULATION vector, the 7^{th} dimension refers to potential targets.

J_2 perturbation effect has been introduced only on the first two arcs, managed by solving the Kepler problem, whereas the last arc duration may be variable, depending on the type of solver adopted. Best solutions have been selected between two different strategies adopted at this stage: single-revolution and multiple-revolution last arc, managed by solving the Lambert problem.

The objective is then to exploit the J_2 effect, by compensating for the $\Delta\Omega$ and $\Delta\omega$ between chaser and target. The effect is maximized by tuning the initial PO. Let PO_{CHASER_0} and PO_{TARGET_0} be the initial parameters for which, without perturbation effect, the optimization program produces an associated cost of $\Delta V_{HOHMANN\_0}$. When perturbation are on, the cost increases to:

$$\Delta V_{PERTURBED\_0} > \Delta V_{HOHMANN\_0}$$

In order to maximize the perturbation effect, it may be useful to track the rates of $\Delta\Omega$ and $\Delta\omega$ and therefore adjust the initial PO. Thence, by properly choosing initial PO and running a new simulation, it can be found the perturbation effects now acts aligning the final PO, in order to have:

$$\Delta V_{PERTURBED\_1} \approx \Delta V_{HOHMANN\_0} < \Delta V_{HOHMANN\_1}$$

Where $\Delta V_{HOHMANN\_1}$ is the cost obtained with adjusted initial PO and perturbation off.

4. Debris capture application

Potential debris orbital parameters have been directly obtained by NORAD real-time database [8] and in the following figure, Ω and ω have been graphed:

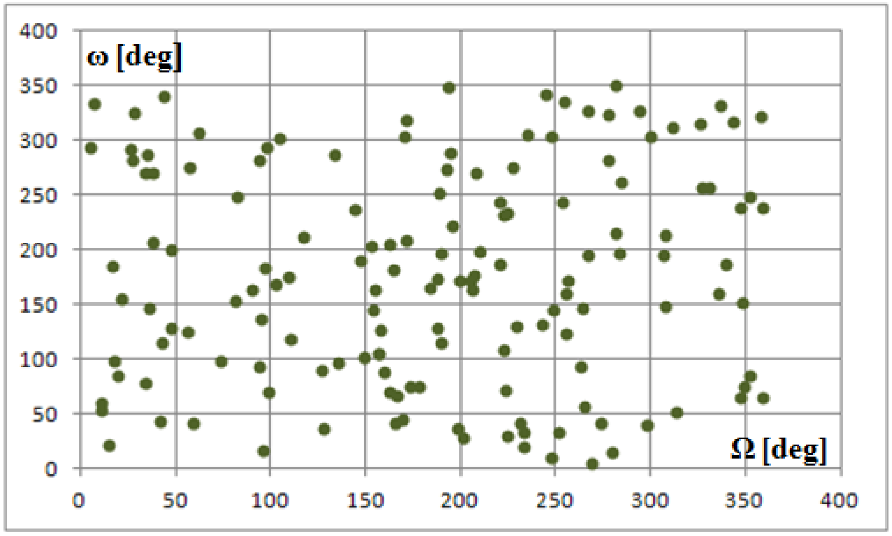

Figure 5: LEO debris population Ω and ω distribution

A random distribution of these parameters, affected by J_2, is favourable for the optimization problem. In fact, in a casual targets population, it results easier to find a proper combination of Ω and ω, which maximizes the perturbation effect.
Next step is now to optimize ΔV associated with a single rende-vous maneuver between two objects in LEO, neither circular nor co-planar. Two sets of simulations have been carried on, both in the ideal and perturbed case. ΔV curve, function of time of flight, has been reported in the following graph:

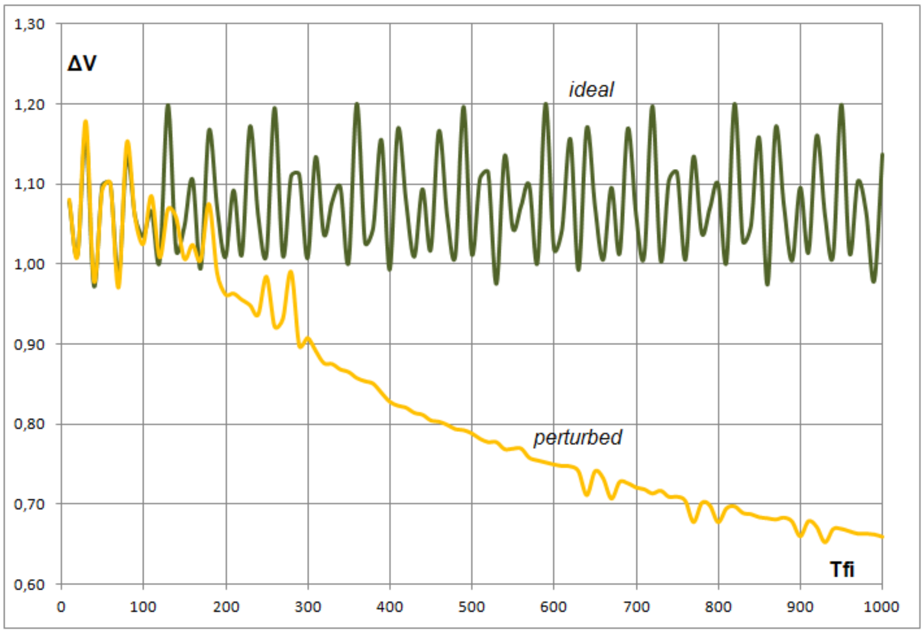

Figure 6: Single-target rendez-vous, ideal vs perturbed

Please note that, from here onwards, T_{fi} and ΔV are dimensionless parameters, with respect to:

$$\sqrt{\frac{R_T^3}{\mu}}\ for\ T_{fi}\ and\ \sqrt{\frac{\mu}{R_T}}\ for\ \Delta V$$

The oscillatory behavior of both curves is directly related to the formulation of the optimization parameters ΔV_1 and ΔV_2. In fact, these two burns are given in the chaser initial plane, whereas only the components ΔV_3 and ΔV_4 are those contributing to the change of plane and alignment with the target. Sometimes the position obtained after the first two impulses is relatively advantageous and leads to low cost options for the last two impulses. In other cases it will be necessary to apply more expensive ΔV_3 and ΔV_4, which lead to local ΔV peaks associated with the overall maneuver.

For short times of flight the perturbation effect does not involve any advantage, since the absolute changes of Ω and ω are too small to be exploited in the optimization of ΔV. However, for higher times of flight, it is interesting to note that the ΔV associated with the transfer sensibly decreases. In this scenario it is possible to accumulate quite consistent $\Delta\Omega$ and $\Delta\omega$ for both the chaser and the target. Consequently, the optimizer will tend to choose solutions in which the chaser moves on intermediate transfer orbits that lead to values of $\Delta\omega$ and $\Delta\Omega$ big enough to compensate for the gap with the target. By conducting further simulations, a negative slope of the curve, in the perturbed case, is obtained until it reaches an asymptotic value corresponding to the minimum ΔV required for the transfer between the two objects, achieved in this case with a time of flight greater than 8000. Values of this kind are however not applicable to debris capture missions, which have as a prerequisite the removal of about tens of objects per year.

5. Multi-target sequence optimization

From a fixed database, grouping the PO vectors referring to potential target debris, it is possible to suitably modify the optimizer, in order to compute the minimum ΔV associated with the rendez-vous sequence, while fixing the time of flight at a constant value of 1000. This can be done by adding up a dimension to the POPULATION vector, with the 7th dimension containing the information about the optimal target to be reached.

$$\mathrm{POPULATION} = [\mathrm{t}_1 - \mathrm{t}_0,\ \mathrm{t}_3 - \mathrm{t}_2,\ \Delta\mathrm{V}_1,\ \Delta\mathrm{V}_2,\ \varphi_1,\ \varphi_2,\ \mathrm{target}]$$

With a potential set of N debris to be captured in a sequence, it is possible to apply the optimizer, with N-1 simulations in succession, where the orbital parameters of the chaser in step N correspond to those of the target reached in the previous step N – 1 (except for the value of true anomaly and the maneuver start time, which need to be updated for all objects, of a value corresponding to the time of flight of each new step). The calculation of the optimal sequence in this case will be limited to a single depth analysis, that is the choice of the target for the step N is made exclusively on the basis of the positions of the entire population in that step, without taking into account possible advantages occurring in future stages. Consequently at each step the optimizer provides for the selection of the target to which is associated the least rendez-vous ΔV at that moment. In reality, however, it may be advisable to reach a target that is associated with a slightly higher ΔV, but which then leads to be in a better position to make the next rendez-vous. If the depth of analysis is equal to the number of objects in the sequence, the global optimum is reached. A problem of this kind is very similar to the so-called Travel Salesman Problem [9]. It is clear that for numerous populations of debris, the computational effort required to compute the global optimal sequence is not sustainable. In this study it was therefore adopted a single-depth strategy. Finally, ten randomly selected objects have been used to perform a comparison between the two different ΔV sequences, obtained in both ideal and perturbed cases.

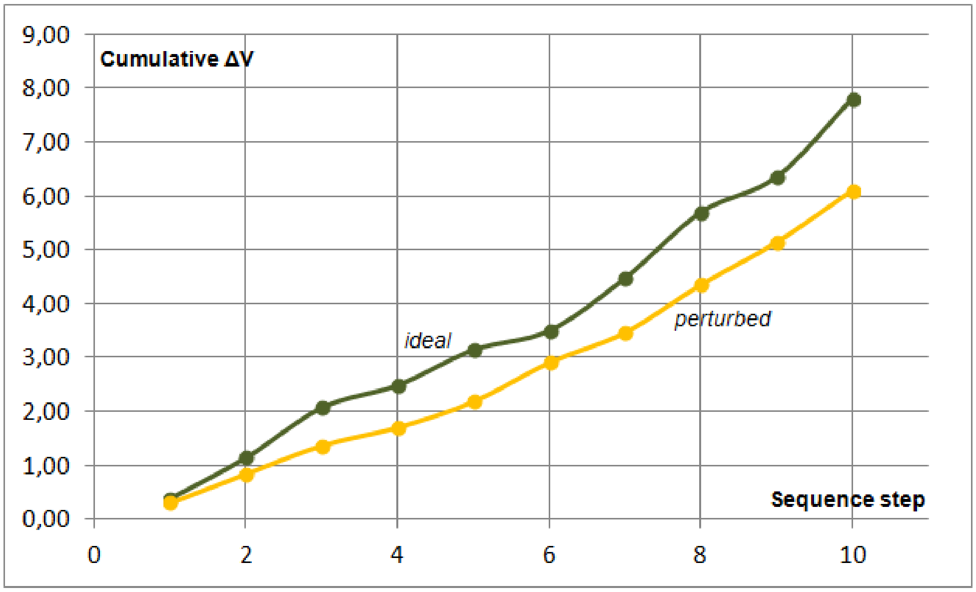

Figure 7: Multi-target rendez-vous sequence, ideal vs perturbed

From the figure above, it can be noted that the J_2 effect contributes to a significant ΔV saving, more than 20%, associated with the rendez-vous sequence of the 10 objects.

6. Conclusions

Multi-target rendez-vous applied to debris capture are gaining a growing interest, in perspective of the implementation of ADR techniques, which are necessary for a proper control of LEO debris hazard. Optimal number of objects to be removed each year is still under evaluation and future research may better address the extent and range of typical ADR reference missions. In the present study it was taken into account a reference value of 10 objects to be removed per year. The main objective was then to optimize a rendez-vous sequence in LEO, by exploiting the J_2 perturbation effect on both chaser and target orbital parameters (Ω and ω), directly affected by the disturbance. Every maneuver composing the final sequence has been modeled as a 4-impulses time fixed rendez-vous, with the objective to minimize ΔV associated with each single step.

J_2 disturbance may be advantageous only for some combination of Ω and ω, so the target shall be accurately selected at the beginning of each new step in the sequence. Nevertheless a debris population with random distribution of Ω and ω ensures the possibility to always be able to find a proper combination of parameters. The optimization strategy involved the use of a hybrid evolutionary algorithm, that was set up in order to search for an optimal solution, expressed by a 7D vector, whose first 6 components uniquely define the single rendez-vous maneuver, whereas the last one identifies the target to be reached.

Simulations run in the frame of the study clearly showed a sensible ΔV saving on the final sequence, when J_2 effect is activated in the optimizer. Yet the optimal sequence finally found is not a global optimum, since the optimizer acts only in a single depth search, whereas the global optimum involves a N-depth optimization strategy with N referring to the number of objects to be captured in the sequence. Further efforts in this field may be therefore addressed toward the increase of analysis depth, taking also into account target positions at times greater than the single rendez-vous fixed time of flight.

In the frame of industrial R&D, CADET project, currently carried on at Aviospace, is primarily aimed to develop an optimal capture mechanism for a single rendez-vous capturing maneuver, with the possibility to extend the range of potential targets up to 6 per mission. This reflect the need to progress in the field of target autonomous recognition and non-cooperative docking, before being able to plan multi-target missions, which will be essential to guarantee a safe orbital environment for the future of circum-terrestrial space exploitation.

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