14º WETE
Workshop em Engenharia e Tecnologia Espaciais

Collision Avoidance Maneuvers Optimization Using Genetic Algorithm

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Abstract. *Collision avoidance maneuvers are crucial for satellite safe operations. The present work aims to use a genetic algorithm to optimize the consumption of fuel in collision avoidance maneuvers (CAMs) in a context where there are dangerous conjunctions between a satellite that have to keep safe and another space object. In this work, the GA's fitness function returns the total maneuver delta-v, however, if the minimal miss distance between the satellite and the secondary object exceeds a established threshold, a penalty is imposed on the performance of the individual. It is considered a burn strategy: an impulse in the in-track direction, and four conjunctions potentially dangerous to be avoided. At final, we contend that efficient collision avoidance maneuver optimization planning can be achieved by using a heuristic algorithm.*

Keywords: Space Situational Awareness; Collision Avoidance Maneuvers Optimization (CAMO); Space Debris.

1. Introduction

The exponential growth in the number of satellites launched in recent years has created an environment full of space debris, especially in LEO orbits. In this scenario, A satellite in operation faces frequent conjunctions with debris that present a high risk of a collision occurring and completely destroying the satellite. To avoid this catastrophe, the permanent solution would be to remove the debris that poses the most danger to space missions, however this is being implemented and presents a high cost to the operator. Therefore, it is most common to use a temporary solution that is a collision avoidance maneuver. In this maneuver, an impulse is provided by the thrusters at an instant prior to the conjunction, which causes the satellite to deviate from its nominal orbit and the debri, and after the TCA (Time of Closest Approach) of the conjunction, a new impulse can be carried out to the return of the satellite to its nominal orbit. Depending on the satellite's mission, a single impulse can be carried out that keeps the satellite still within the envelope of its nominal orbit.

To determine the maneuver that will be carried out, operators look for those that save fuel. This problem soon becomes a research front to find maneuvers with the minimum total impulse (ΔV_{total}). The optimal collision avoidance problem has been solved using several optimization methods. Some studies have used global optimization schemes such as evolutionary algorithms, while others have used direct and indirect optimization techniques.

One of the first approach to the problem was using the method Rapidly exploring Random Trees (RRT) Frazzoli (2003) that is a heuristic method and the solution was not claimed to be optimal. In sequence, following the use of heuristic methods, it was solved the optimal collision avoidance problem using Genetic Algorithm Kim, Kim e Kim (2012), at the same year Huang et al. (2012) used a hybrid method implementing the Legendre Pseudospectral Method to discretize the state dynamics along with other constraints to formulate the nonlinear programming problem, which was then solved using the Particle Swarm Optimization technique.

Another optimization methods also was used, as an eigenvalue method Bombardelli, Ayuso e Pelayo (2014) and a gradient method Patera e Peterson (2003). Using a indirect method and an eigenvalue method Slater, Byram e Williams (2006) solved for a single, energy-optimal collision avoidance maneuver in formation flying while using Clohessy-Wiltshire equations, and in this paper the return of the satellite back to its nominal orbit was not considered. Another work that implemented a indirect method was Zimmer (2005). A time optimal solution for ensuring collision avoidance using aerodynamic drag was presented by Omar e Bevilacqua (2020).

Direct method also have been used to find optimal solutions for collision avoidance maneuvers problem Sales (2013), Martinson (2009), however these do heavily depend on the initial guesses and can lead to locally optimal solutions for non-convex problems. In that case, convex formulations to find the global optimum have been used for solving formation flying problems of for finding a set of avoidance maneuvers have been studied in Mueller e Nordström (2008), Armellin (2021), Dutta e Misra (2022). And, in particular, Benedikter e Zavoli (2019) formulated a convex rendezvous problem using Tschauner-Hempel equations and convex constraints, the problem was formulated as a successive second-order cone programming problem, and the uncertainty related with the state variables was neglected.

Mueller e Nordström (2008) posed a problem for maintaining two satellites in close proximity, as a linear programming problem. Since the feasible region for the small satellite was the entire space except the avoidance region around the main satellite, it was dealt with using the rotating hyperplane method. Robustness was incorporated by implementing the same avoidance constraint for a number of uncertain initial relative states.

Multi-impulsive convex optimization problem concerning only the avoidance maneuvers was solve using successive convexification in an iterative process in Armellin (2021). The state dynamics were dealt with using Differential Algebra and successive linearizations. The collision probability was calculated by projecting the combined error covariance onto the encounter plane at the time of closest approach ad the linearized squared Mahalanobis distance was found using an optimization sub-problem.

The effects of certain orbital, control and uncertainty parameters on the optimal ΔV requirement were also studied by Dutta e Misra (2022, 2023a) presented a comparison between the convex and non-convex formulations to solve the complete problem of collision avoidance and return of the satellite back to its nominal orbit. Nonlinear propagation of uncertainty has been implemented while determining the avoidance and return maneuvers in fuel-optimal manner in Dutta e Misra (2023b), where non-Gaussian nature of the evolved uncertainty distribution for designing the optimal set of avoidance maneuvers was studied.

An analytical energy-optimal method implementing indirect optimization with constant covariances to handle low-thrust short-term encounters was presented by Vittori et al. (2022). The study did not take into consideration the return of the satellite to the nominal orbit, so the avoidance constraints or the final conditions were enforced using the bidimensional collision probability and the miss distance. The solution from the energy-optimal problem had then been used to solve the fuel-optimal problem.

In Rajasekar (2017) was studied the collision avoidance problem along with the re-insertion of the satellite back to the nominal orbit using Self-Adaptive Differential Evolution technique. Another heuristic method was implemented in Lee, Park e Park (2017) where was presented a suboptimal continuous control algorithm for collision avoidance maneuvers.

In this paper is presented a method for optimizing fuel consumption in the context of collision avoidance maneuvers using evolutionary methods, in this case, genetic algorithm. The fitness function use the minimal miss distance between the satellite and the secondary object from all conjunctions within the time of simulation, and whether one of these values exceeds the threshold, a penalty is imposed. It is considered a burn strategy: an impulse in the in-track direction, and four conjunctions potentially dangerous to be avoided.

2. Methodology

In this work, the recently launched Brazilian Air Force satellite Carcará 1, which belongs to the Lessonia constellation, was chosen. Orbital data for this satellite follows in the Table 1.

Table 1. Carcará-1 Orbital Elements.

e	0.00089140
a	6902.367 km
ω	243.3362º
i	97.5290º
Ω	97.4127º
M_0	241.0308º

A conjunction between two space objects is characterized as an event where two objects have a miss distance value between them less than a certain limit, which can be 5 km, 10 km, 20 km and others. In this article it will be considered a threshold of 5 km. A scan is carried out looking for conjunctions that have a minimum approach distance of less than 5 km (threshold established in this work) and a probability of collision greater than 10^{-7}. This scan was carried out using the SOCRATES Plus system, available on the Celestrak domain.

In this sense, in Table 2 there are 4 conjunctions involving the Carcará-1 satellite. During each event, the instant of time in which the miss distance presents the lowest value is called TCA - Time of Closest Approach.

Table 2. Conjunctions between the satellite and space debris.

Object NORAD ID	TCA	MD
34221	15/12/2022 14:15:49.80UTC	4.811 km
39316	16/12/2022 07:42:30.00UTC	2.084 km
18214	17/12/2022 16:14:34.90UTC	3.511 km
43838	17/12/2022 15:27:48.40UTC	2.793 km

The maneuver to mitigate the risk related to conjunctions will be an impulsive maneuver, where a delta-V will be carried out at an instant of time prior to the conjunctions. The thrust direction will be in the along-track direction. The instant of time and magnitude of the impulse will be determined to reduce fuel consumption, in this case the delta-V module, and still distance itself from the 4 objects that will pass close to the satellite. With regard to distance, it is desirable that the minimum distance between the satellite and the secondary object (miss distance) increases to a value greater than 20 km with the maneuver.

To calculate the orbital propagation of the satellite and other orbital objects, it was implemented a J2 orbital propagator considering the secular terms.

Thus, performing a scan in the time domain, calculating the position vector of the satellite and a database of space debris, it is possible to calculate the miss distance, which is the modulus of the difference vector between the position vectors of the satellite and the debris.

$$MD = |\vec{r}_{sat} - \vec{r}_{debri}| \tag{1}$$

Hence, a genetic algorithm was implemented to find an instant of time prior to the TCA of the first conjunction (15/12/2022 14:15:49.80UTC) and the impulse module that will be applied in the direction of the tangential vector to the satellite's orbit (Along-Track in the LVLH frame). Thus, there are two random variables for the genetic algorithm, which are: the instant of the impulse and its magnitude.

2.1. Genetic Algorithm

The process starts with the creation of a random population of 100 individuals that take into account a instant of time of the impulse and a impulse magnitude, both obtained randomly within domains established a priori in the simulation. The domain of the instant of the impulse is between 1 hour and 10 days before the first conjunction. And the impulse magnitude have a domain between zero (no maneuver) and 5 km/s^3.

The random variables of each individual are transformed into binary vectors that would be the chromosomes of each individual, after this procedure the algorithm allows the individuals crossover and generate new individuals, during this process there is a chance of a mutation occurring in the individuals. At the end, the individuals with best performance in fitness function are select as best individuals, presenting higher chance to survive. The algorithm realizes 500 generations. Where crossover rate is 25% and the mutation rate is 1%, the flow chart of the algorithm is shown at Figure 1.

2.2. Fitness function

Given a Δt that represents the difference between the instant of the first conjunction and the instant of application of the impulse, the analytical propagator is used to calculate the position and velocity vectors of the satellite in that previous instant. Then the impulse is applied and the vehicle's orbit is propagated again until the instants that previously occurred the conjunctions.

For each conjunction studied, a new miss distance is then calculated considering the trajectory after the impulse is carried out. If the miss distance value is greater than the threshold of 5 km and considered that the conjunction was avoided, or rather, that the risk was mitigated, thus configuring what is called Risk Mitigation Maneuver by operators.

Based on that, the value of the fitness function is given by the ΔV applied plus penalties for each unavoided conjunction.

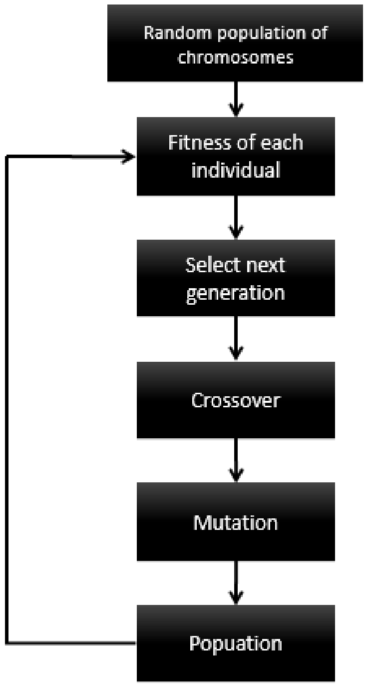

Figure 1. Genetic algorithm's flow chart

$$fitness = \Delta V + n \times 1000 \tag{2}$$

where n is the number of conjunctions with miss distance ¡ 20 km (unavoided).

In this way, the maneuver that presents the lowest value of ΔV and that all miss distances of the conjunctions calculated with the satellite trajectory after the impulse are greater than the threshold of 5 km is sought as an optimized system solution.

3. Results and discussion

It was generated 5 different initial populations and the proposed genetic algorithm was imposed on each one. Below in Figure 2 the convergence curves for each of the populations are presented. It can be seen that after 500 generations, optimized solutions to the problem were obtained that presented very close ΔV values ($\Delta V = 2.4414 \times 10^{-3}$).

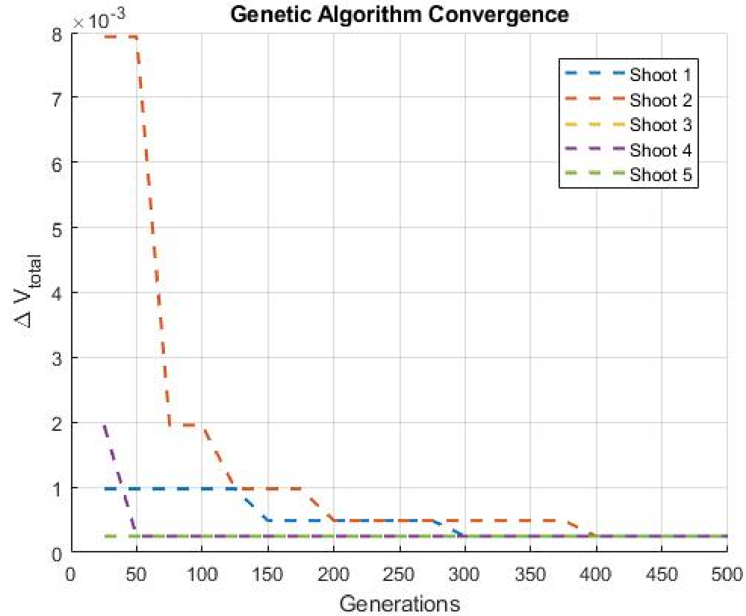

Figure 2. Genetic Algorithm convergence

The optimized solution for each initial population is shown in Table 3, where it can be seen that the solutions found present the same impulse magnitude value, however they present different time instants for carrying out the maneuver. This may lead to the fact that the instant of application of the impulse does not have a significant impact on the solution when compared to the magnitude of ΔV.

Table 3. Optimized solutions founded for each initial population

	$\Delta t(days)$	$\Delta V(m/s)$
Shoot 1	4.2568	1.8750
Shoot 2	4.2568	1.8750
Shoot 3	4.4734	1.8750

So, in short, it is presented different values for Δt. Following a more practical approach, from the point of view of the satellite operator, the result found shows flexibility in the moment of impulse application, which provides more time for the operator to make the decision.

With the application of the impulses, the values of MD changed, below it will be shown the values found for the first solution found ($\Delta t = 4.3094$ days and $\Delta V = 2.4414 \times 10^{-3}\ km/s$) in Table 4.

Table 4. Conjunctions between the satellite and space debris after the realization of the maneuver: $\Delta t = 4.3094$ **days and** $\Delta V = 2.4414 \times 10^{-3}\ km/s$

Object NORAD ID	TCA	MD
34221	15/12/2022 14:15:49.80UTC	81.329 km
39316	16/12/2022 07:42:30.00UTC	23.380 km
18214	17/12/2022 16:14:34.90UTC	26.511 km
43838	17/12/2022 15:27:48.40UTC	29.157 km

4. Conclusion

Therefore it is concluded that the use of a heuristic method as the genetic algorithm to optimize orbital maneuvers was a success since it was possible to optimize a collision avoidance maneuver.

In the work there was convergence of the genetic algorithm for the same speed increment, however the fitness function presents local minima when the time is varied. Which helps in the operation of the satellite.

There are different approaches in the literature to find solutions that optimize fuel consumption in collision avoidance maneuvers due to the arbitrary content of this need. Given this scenario, this research topic has taken its place in academia. In the continuation of the work, the inclusion of disturbances such as J2 and drag will be addressed, with a focus on LEO satellites.

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