Abstract

In the Winter of 2009, the CHOPIN (Canada, Holland, Japan orbit Investigator Network) team of the Japan Aerospace Exploration Agency (JAXA) participated in the fourth Global Trajectory Optimization Competition (GTOC4). This time, the objective was driven by the question: “How to maximize the relevance of a rendezvous mission to a given NEA by visiting the largest set of intermediate asteroids?” For the competition, the spacecraft had to be launched from Earth with a hyperbolic excess velocity of up to 4 km/s. Then, using electric propulsion, the spacecraft had to flyby a maximum number of asteroids from a given list and rendezvous with a last one within 10 years. The mission was constrained to have a launch window between 2015 and 2025, and the spacecraft wet mass was assumed to be 1000 kg, with a spacecraft specific impulse of 3000 s and a thrust level constrained to 0.135 N. Finally, each asteroid could only be visited once. The performance index to be maximized was the number of asteroids and the final mass of the spacecraft. In this paper, we go over the methods used, results obtained and lessons learned.

1 Introduction

The Global Trajectory Optimisation Competition (GTOC) was initiated in 2005 by the Advanced Concepts Teams of the European Space Agency (ESA). The GTOC problems are traditionally global optimisation problems, i.e. complex optimisation problems characterized by a large number of local optima. By global optimisers, we mean the use of pruning methods to reduce computing time whereas local optimisers are used to determine best initial conditions to find the global optimum.

Objectives of the competition are to propose a problem such that:

- The design space is large and leads to an important number of local optima.
- Even though complex, the problem can be solved within the 4-week period allowed for the competition.
- The formulation is simple enough so that it can be solved by researchers not experienced in Astrodynamics.
- Even if some registered teams have already developed their own optimisation tools for interplanetary missions, the problem specificities make it new to all teams.

We first describe the approach and methods used to solve the task assigned. The team started backwards by looking at rendezvous candidates for the last asteroid. The potential candidates were found by taking all asteroids from the given set having an orbit “similar” to that of the Earth, and solving multi-revolution Lambert problems with 9, 10, and 11 full revolutions. Then, using some pruning methods on the given Near Earth Asteroid set and the exponential sinusoid Lambert method, other asteroids that could be met on the way were identified. After finding some first estimates, an optimization method using a combination of nonlinear programming and collocation was used. Unfortunately, the results couldn’t completely be validated but provided useful steps for such optimization problems.

2 Global Trajectory Optimization Competition

2.1 Competition History

The GTOC challenge was first organized in 2005 by the Advanced Concepts Team of the European Space Agency. This first competition was to maximize the change in the semi-major axis of the asteroid 2001 TW229 subsequent to the impact of an electric propelled spacecraft. The winner of the competition was the Outer Planets Mission Analysis Group at the Jet Propulsion Laboratory, which organized the next challenge. In 2006, the GTOC2 was to find the best
possible spacecraft trajectory, or flight path, for visiting a sequence of asteroids. GTOC2 was won by the Aerospace Propulsion Group of the Dipartimento di Energetica of the Politecnico di Torino. The Italian team then organized the GTOC3 to design a multiple near-Earth asteroid (NEA) rendezvous with return to the Earth using electric propulsion. Le Centre National d’Etudes Spatiales proved to have the best design for this one, and produced the past competition described in the following paragraphs.

2.2 GTOC 4: Problem Description

The current problem of interest is stated as follows:

“How to maximise the relevance of a rendezvous mission to a given NEA by visiting the largest set of intermediate asteroids?” The following assumptions were given:

- The launch needed to be from Earth.
- The task was to flyby a number of asteroids from a given list.
- The spacecraft had to rendezvous with the last asteroid of the same list within 10 years of departure.
- Gravity assist maneuvers were not allowed during the mission.
- The spacecraft was equipped with an electric propulsion system.

The reasoning behind these assumptions is that the use of electric propulsion provides an optimal control formulation for the GTOC4 problem when a sequence of asteroids is given. With the high number of feasible asteroids sequences, the problem implies a large number of local optima.

2.3 GTOC 4: Spacecraft and Trajectory Constraints

A few constraints needed to be taken into account. The spacecraft needed to be launched from Earth, between 2015 and 2025, with a hyperbolic velocity of up to 4.0 km/s. The spacecraft had to flyby a maximum number of NEAs taken from the given list, and then rendezvous with a last asteroid of the same list. Each asteroid couldn’t be visited more than once during the mission, and the flight time couldn’t exceed 10 years.

In terms of spacecraft performance, the spacecraft had a fixed initial mass of 1500 kg (not affected by the launch \(v_{\text{inf}}\)), where the spacecraft dry mass was set to 500 kg, leaving 1000 kg as propellant. The spacecraft specific impulse was set constant to 3000 sec, and its thrust level could take any value from 0 to 0.135 N with no constraint on the thrust direction, and independent of the spacecraft – Sun distance. The spacecraft mass was to vary only during thrusting periods.

2.4 GTOC 4: Performance Index

The primary index to be maximized was the number of visited asteroids

\[
J = \sum_{j=1}^{n} \alpha_j,
\]

where \(n\) is the total number of NEAs and \(\alpha_j\) is the number of times that asteroid \(j\) has been visited, \(\alpha_j \in \{0, 1\}, j = 1...n\).

For the final rendezvous, the asteroid could only have \(\alpha = 0\). Hence, \(J\) would not exceed \(n - 1\). If two solutions were associated with the same number of visited NEAs, a secondary performance index was the final mass of the spacecraft to be maximized, \(K = m_f\), with \(m_f = 500\) kg.

3 Initial Estimates Methods

In order to tackle this challenge, the first focus was put on the rendezvous with the final asteroid. Potential candidates were found by taking all asteroids from the set that have an orbit “similar” to that of Earth. Initial estimates for the
launch and arrival date came from solving simple multi-revolution Lambert problems with 9, 10 or 11 full revolutions. Then, for these combinations of launch and arrival dates with the lowest velocity at the asteroid, while satisfying the 4 km/s constraint on $V_{\text{inf}}$ at Earth:

- All positions were propagated backwards in time, from that initial date towards the launch date.
- Potential asteroid flybys were found by looking at the distance all asteroids had to the spacecraft’s instantaneous Keplerian orbit, within a small time interval from the initial time.
- If some asteroids were found to be closer to the spacecraft’s orbit than some threshold distance, the one closest to Earth's orbit were selected.
- Otherwise, if no asteroids were found to be close enough, the length of time was increased. Initially, these time intervals were set to 2 weeks, and were increased by 2 weeks in case no asteroids were found. The search method is represented in Fig. 1.
- The threshold distance varied with time, and was based on the maximum change in orbital energy the ion engine could accomplish during the given time interval.

![Figure 1: Initial estimates search method.](image)

In case an asteroid was selected for a flyby, we solved the exponential sinusoid Lambert-problem from the initial asteroid to the position of the potential flyby asteroid. This lambert-procedure involves a free design parameter (usually called $k_2$), which was optimized together with the transfer time, such that the impulsive velocity change required at the flybys was minimal.

If that minimum DV was found to be larger than the maximum DV that could be achieved by the ion-engine during the transfer time to that asteroid, the asteroid was discarded and the procedure restarted. This whole process was repeated until the total transfer time (from the last asteroid to the current asteroid) was about 9 years. After that time, focus was put on going to Earth. This part of the trajectory was optimized using the same low-thrust Lambert-problem approach.

We found that the Earth was quite hard to reach for some final asteroids and initial rendezvous date combinations. Therefore, we simply tried all asteroids and rendezvous dates found initially, until we had a set that both had many asteroid flybys and a feasible Earth leg.

4 Optimisation

For the final optimisation, all positions were propagated forward in time again, from the launch to rendezvous. Although this time, instead of exponential sinusoids, the following method was used.

For each asteroid-asteroid leg, one additional asteroid was taken from the set, and the two connecting arcs were optimized for maximum end mass at the third asteroid. For each trio, the positions of the first and last asteroid were kept fixed, while the position of the central asteroid was allowed to vary. When the minimum mass was found within 1 m/s, the position of the central asteroid was fixed. The next asteroid from the set was added, and the (optimized) velocity at the former central asteroid was added as a constraint. The position of the former third asteroid was released, and the next two legs were optimized. The optimisation strategy is illustrated in Fig. 2. Note that this makes the final mass AND the transfer times and positions of the flyby asteroids to be optimized.

For the Earth leg, the position of the third asteroid-asteroid was kept fixed, while the central asteroid and the Earth were allowed to move. For the leg to the final rendezvous asteroid, only the position of the first asteroid was kept fixed, while the positions of the central asteroid and the rendezvous asteroid were allowed to vary. This proved somewhat easier to meet the (more strict) constraints on these two bodies, i.e. the maximum allowed $V_{\text{inf}}$ of 4 km/s at Earth, and the requirement that $V = 0$ at the rendezvous asteroid.

We tried a variety of optimization methods:
• Using an indirect method, which proved to be quite hard to apply to this problem.
• A developed by [3], but which proved to be too time consuming, and had poor convergence properties.
• Finally, one that could converge in a reasonable time, which was a combination of nonlinear programming and collocation [1]. Optimizing each set of initial estimates with this method required about 11 hours.

5 Results

The following results were achieved:

• Launch date: MJD 59857.4913
• Number of asteroids flown by: 25
• Final Rendezvous asteroid: 2008 UA202
• $V_{inf}$ at Earth: 3.995 km/s
• Final mass: 1436.4247 kg
• Total time of flight: 10.1205 years

The trajectory is shown in Figs. 3 a and b, while the mass and thrust profiles are shown in Fig. 4. The list of visited asteroids is shown in Table 5.

6 Discussion and Conclusions

The Fourth Global Trajectory Optimization Competition was to maximise the number of asteroid flyby for a rendezvous mission to a given NEA.
Finally, the result was discarded due to the constraint on the maximum mission duration, 10 years, that could not be met. There is a number of improvement that could be done regarding the method followed. The team did not have time to validate the final result, and, later on, found that one of the methods discarded too many asteroids. Hence, it is easy to see that thrust and mass profiles of the final solution would have been improved.

However, all team members learned a great deal on astrodynamics, low thrust, and optimisation methods. Also thank you to our advisors at JAXA/ISAS. The international experience was also certainly beneficial. We all look forward to hear about the 5th GTOC.

References

