17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 285

Low-thrust Earth-Saturn trajectory with multiple gravity assists and unpowered orbit insertion

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Abstract

The giant planets have a special place in our quest for learning about the origins of our planetary system and the search for life. On its mission to Saturn, Cassini discovered water plumes containing complex organic molecules emanating from the sixth largest moon of Saturn, Enceladus. This discovery suggests that Enceladus and other inner large moons of Saturn (ILMs) might provide a suitable environment for the development of life. In order to improve our understanding of the moons of Saturn and other giant planets, dedicated exploration missions are required. However, achieving an orbit around Saturn with impulsive maneuvers is very costly in terms of propellant consumption due to the large hyperbolic excess velocity on arrival. Furthermore, the ILMs are deep inside the gravitational well of Saturn, further increasing the propellant cost. This study presents a strategy to reach Saturn with a low hyperbolic excess speed leveraging the high efficiency of low-thrust (LT) propulsion in combination with multiple gravity assist (GA) maneuvers to drastically reduce the propellant budget. The reduced relative speed enables an unpowered orbit insertion with a Titan flyby. This study follows up on a previous work in which a combination of LT propulsion and Jupiter GA was used to lower the relative arrival speed to 1 km/s. The same arrival conditions are adopted in the present work, but the launch mass is increased to accommodate the propellant required for subsequent transfers inside the Saturn system, while the launch energy is substantially reduced using flybys with inner planets. A multi-objective global optimization tool using an approximate dynamical model is used to quickly search for time and fuel-optimal trajectories, and determine optimal sequence of GA maneuvers. Next, the trajectory that best meets the mission requirements is selected and refined further with a direct optimizer. With an initial spacecraft mass of 1500 kg, characteristic launch energy of 27.04 km^2/s^2, and 640 W of electrical power for the thruster, it is possible to reach Saturn in 12.34 years (from January 21st 2028 to May 24th 2040) with 1014 kg arrival mass via an Earth-Venus-Venus-Earth-Saturn trajectory. The power required by the electrical engine (PPS X00 Hall thruster) can be supplied by radioisotope thermoelectric generators, hence avoiding the limitations from the reduced solar flux far from the Sun.

Keywords: Giant planets, Saturn, inner large moons, low-thrust propulsion, multi-gravity assists, optimal control

Acronyms/Abbreviations

Low thrust (LT), Gravity assist (GA), Inner Large moons (ILMs), Orbit insertion (OI), Nonlinear Programming (NLP), Earth-Venus-Earth-Earth-Saturn (EVEES), Earth-Venus-Venus-Earth-Saturn (EVEES), National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory (JPL), Interior Point Optimizer (IPOPT).

1. Introduction

Exploration of the moons of the gas giants is vital in our quest for extraterrestrial life [1]. For example, the Cassini probe discovered water plumes emanating from the south pole of Enceladus, Saturn's sixth largest moon. Once considered a completely frozen world, Enceladus is now believed to host a sub-surface ocean, which might provide a suitable environment for life [2]. In fact, the analysis of the plumes by NASA revealed the presence of complex organic molecules containing carbon, hydrogen, oxygen, and nitrogen, crucial elements for making amino acids, the building blocks of proteins. This discovery suggests that adequate environments for sustaining life may exist on Enceladus and the other Inner Large Moons (ILMs) of Saturn (i.e., Mimas, Tethys and Dione).

We could improve our knowledge of the ILMs of Saturn by placing spacecraft in orbit around them. This presents two challenges. First, achieving Saturn orbit insertion (OI) with impulsive maneuvers demands a costly burn due to the large hyperbolic excess velocity on arrival. Second, the inner moons, of highest scientific interest, are deep inside the gravitational well of Saturn, further increasing the propellant cost.

Cassini/Huygens, the only spacecraft to date that entered orbit around Saturn, required an OI impulse of 622 m/s consuming 800 kg of propellant [3], and 320 kg for the subsequent pericenter raising. Deep-space maneuvers and course corrections before OI increased the mass budget by almost 1000 kg [4]. Overall, these maneuvers consumed over 35% of the initial spacecraft mass (5655 kg). Cassini did not enter orbit around any moon, as the cost would have been prohibitive. A completely different approach is required to explore the inner moons in detail.

Our group is developing a strategy to tour the inner moons of Saturn leveraging low-thrust (LT) arcs with electric propulsion to eliminate or reduce drastically the need for impulsive maneuvers. The high efficiency of electric thrusters enables large reductions in the propellant budget. This paper focuses on a strategy to reach Saturn with very low hyperbolic excess velocity, and is a follow-up to [5]. The reduced relative speed enables unpowered OI with a Titan flyby [6]. Subsequently, it is possible to tour of the moons via low-thrust transfers between libration point orbits of the 3-body problems involving the spacecraft, Saturn and each one of its satellites [7].

In [5], we presented a gradient-based steering law which reduces the relative arrival velocity at Saturn using deep-space LT maneuvers. If the hyperbolic excess velocity is lowered to 1 km/s, unpowered OI becomes possible. The study was a proof-of-concept, focusing on relative speed reduction, rather than a complete trajectory optimization. For example, we assumed a small launch mass of 1000 kg (for a mission of this type) with a direct Earth-Jupiter transfer in the first leg (resulting in an elevated launch energy of 67.25 km^2/s^2). Moreover, we did not enforce phasing constraints directly from the ephemeris of the planets. The transfer to Saturn took 13 years and consumed 367 kg of propellant (a mass fraction of 0.367), assuming motor performance compatible with NASA's Evolutionary Xenon Thruster, NEXT, (thrust level: 25 mN, specific impulse: 1400 s, input power: 610 W) [8].

In this study, we build on the results of the previous work [5] to bring the mission concept closer to practical realization. In particular, we enforce phasing constraints and use multiple gravity-assist (GA) maneuvers with Venus and Earth to lower the departure energy substantially. Moreover, we increase the launch mass to 1500 kg to enable ulterior inter-moon transfers inside the Saturn system, while maintaining a flight time comparable to the 13 years achieved in [5]. Due to reduced solar flux at Saturn, we rely on radioisotope generators (RTGs) as energy source for the electric thruster. This limits the available power and, consequently, the thrust magnitude. To better accommodate this constraint, we base our analysis on the performance of the PPS X00 Hall thruster [9], which delivers a better thrust-to-power ratio than NEXT for our particular application (e.g., 40 mN of thrust at 650 W input power).

2. Methodology

As stated previously, the target of this study is to find an optimal LT multi-gravity-assist trajectory to Saturn that meets the mission constraints and minimizes both flight time and propellant consumption. As the optimal number and sequence of GA maneuvers are unknown, this problem is treated as a hybrid optimal control problem and is solved using a two-step approach.

In the first step (Step 1 hereafter), we rely on a multi-objective global optimization tool (MOLTO-IT [10]) to quickly explore the global solution space and determine the integer optimization variables (i.e., the number and sequence of GAs). MOLTO-IT uses genetic algorithms with an approximate dynamical model that assumes a planar trajectory built from logarithmic spiral segments. The maximum thrust cannot be constrained in MOLTO-IT, as it is determined *a posteriori* from the properties of the spirals. To mitigate this issue, the total impulse of each leg is constrained below what the thruster can deliver in the duration of the leg. MOLTO-IT returns a Pareto-front representing the trade-off between total transfer time and propellant mass fraction, from which the approximate trajectory best adapted to the mission requirements can be selected.

The best candidate obtained in Step 1 establishes the flyby sequence, as well as initial guesses for the launch date and evolution of the state vector. It is refined in the second step (Step 2), with a higher-fidelity optimization method including a more general dynamical model. Step 2 also assumes a 2D trajectory, contained in the ecliptic plane. Furthermore, the spacecraft's motion is governed exclusively by the gravitational attraction of the Sun (except during the GA maneuvers, which are assumed instantaneous and controlled by the planet's gravity) and the thrust of the engine. The dynamical model, which describes the evolution of heliocentric position ($\mathbf{r}$) and velocity ($\mathbf{v}$) vectors, as well as spacecraft mass (m) during the interplanetary segments, is expressed mathematically as

$$\begin{cases} \dot{\mathbf{r}} = \mathbf{v} \\ \dot{\mathbf{v}} = -\frac{\mu}{r^3}\mathbf{r} + \frac{T}{m}\hat{\mathbf{u}} \\ \dot{m} = -\frac{T}{I_{sp} g_0} \end{cases} , \tag{1}$$

μ being the gravitational parameter of the Sun, T the thrust magnitude, I_{sp} the specific impulse, $g_0 = 9.81\ m/s^2$ and $\hat{\mathbf{u}}$ the unit vector in the direction of the thrust.

The optimization strategy used in Step 2 is a direct method, which converts the equations of motion (Eq. (1)) into dynamical constraints using Hermite-Simpson collocation scheme [11]. Also, the optimization problem is transformed into a nonlinear programming (NLP) problem, and includes other constraints such as boundary conditions, thrust limits, and maximum transfer time. To compute phasing, ephemeris from NASA JPL [12] are used to determine the position and velocity of planets. The legs of the trajectory (segments between GA maneuvers) are connected with linkage constraints to enforce continuity of trajectory and mass. Using the selected Step 1 trajectory as the initial guess, the NLP problem is solved with the IPOPT package [13], with a weighted combination of transfer time (t_f) and arrival mass (m_f) as cost function (J), i.e.,

$$J = -m_f + w * t_f \ , \tag{2}$$

where w is the weighting variable.

In addition to changing the value of the weighting variable in Eq. (2), we also attempted to reduce the thrust as far as possible. For each thrust setting, the specific impulse was taken from the performance envelope of the PPS X00 Hall thruster [9]. The three thrust settings shown in Table 1 were tested in Step 2 (Step 1 always uses setting #1).

Table 1. Selected thrust settings from the PPS X00 thruster [7].

Setting #	Thrust level (mN)	Specific impulse (s)	Input power (W)
1	50	1400	850
2	40	1450	650
3	36	1400	640

3. Results and Discussion

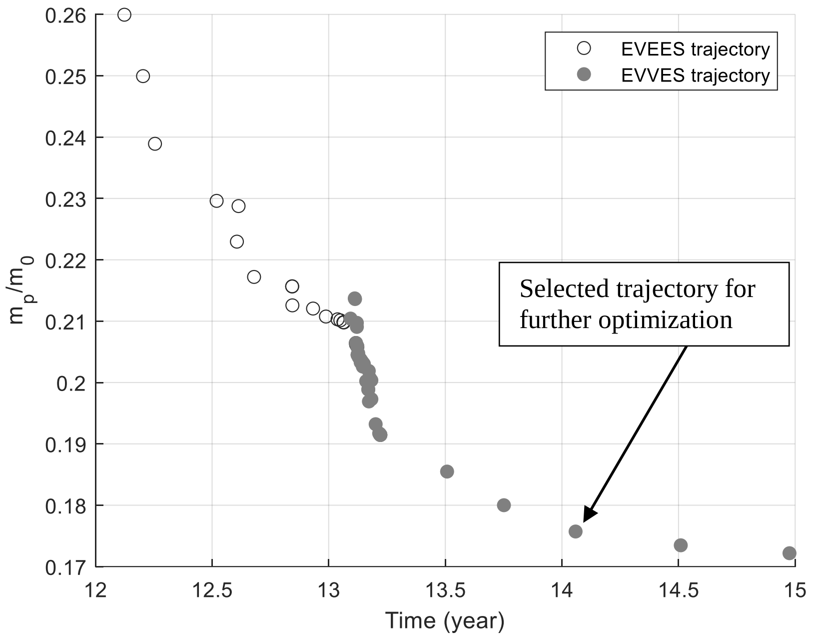
Using a launch window from 2023 to 2050, 5.2 km/s initial hyperbolic excess speed, 1 km/s arrival relative velocity and 15 year maximum transfer time, the multi-objective global search (Step 1) returned the Pareto front shown in Fig. 1. Two families of trajectories were obtained: Earth-Venus-Venus- Earth-Saturn (EVVES) and Earth-Venus-Earth-Earth-Saturn (EVEES). We set the number of generations to 500, with a population size of 100 individuals in the genetic algorithm configuration.

The EVVES solutions are characterized by lower propellant consumption and longer transfer times than the EVEES trajectories. When used as initial guesses in Step 2, EVEES trajectories yield converged solutions only for the highest thrust setting in Table 1 (50 mN). On the other hand, EVVES trajectories are compatible with all three settings (from 36 to 50 mN). The trajectory indicated in Fig. 1, corresponding to a transfer time of 14.06 years and a propellant mass fraction of 0.176, strikes a good compromise between the two objectives (minimal propellant consumption and transfer time) and has been further optimized with the direct method (Step 2). A range of solutions corresponding to different weights in the objective function (Eq. 2) and thrust settings (Table 1) are reported in Table 2. The solution in boldface (Solution 7) represents the best compromise between propellant mass fraction, flight time and the input power level. Fig. 2 illustrates the full trajectory and a zoomed view of its inner portion, while Fig. 3 highlights the thrust arcs (thick solid lines) and coast segments (dotted lines). The thrust magnitude and thrust angle histories are plotted in Fig. 4, where an angle of zero corresponds to circumferential thrust and 90º is the radial direction.

This refined solution is a significant improvement with respect to [5]. It is more realistic, since the actual trajectories of the planets (phasing constraints) have been taken into account, unlike in [5]. Furthermore, the EVVES trajectory lowers the launch energy significantly from 67.25 km^2/s^2 in [5] to 27.04 km^2/s^2, while requiring a shorter time to reach Saturn (12.34 years vs. 13 years in [5]). Furthermore, the higher arrival mass (1014 kg vs. 633 kg in [5]) accommodates a larger propellant mass for an eventual tour of the moons [7]. Moreover, this improvement has been achieved with very similar power constraints as in [5] (640 W in this study and 610 W in [5]).

Table 2. Solutions obtained after optimization with a direct method (Step 2).

Solution #	Thrust setting #	Weighting parameter (kg/year)	Transfer time (year)	Propellant mass fraction	Launch date	Arrival date
1	1	0	14.19	0.3352	16 Feb, 2023	27 Apr, 2024
2	2	0	14.81	0.3522	01 Jan, 2023	23 Oct, 2037
3	2	188.36	11.95	0.3697	20 Jan, 2028	02 Jan, 2040
4	3	0	14.84	0.3106	19 Feb, 2023	22 Dec, 2037
5	3	188.36	11.78	0.3833	02 Feb, 2023	20 Nov, 2034
6	3	156.97	11.98	0.3943	02 Feb, 2023	20 Nov, 2034
7	**3**	**117.72**	**12.34**	**0.3243**	**21 Jan, 2028**	**24 May, 2040**



Selected trajectory for further optimization

Fig. 1. Pareto front obtained after Step 1.

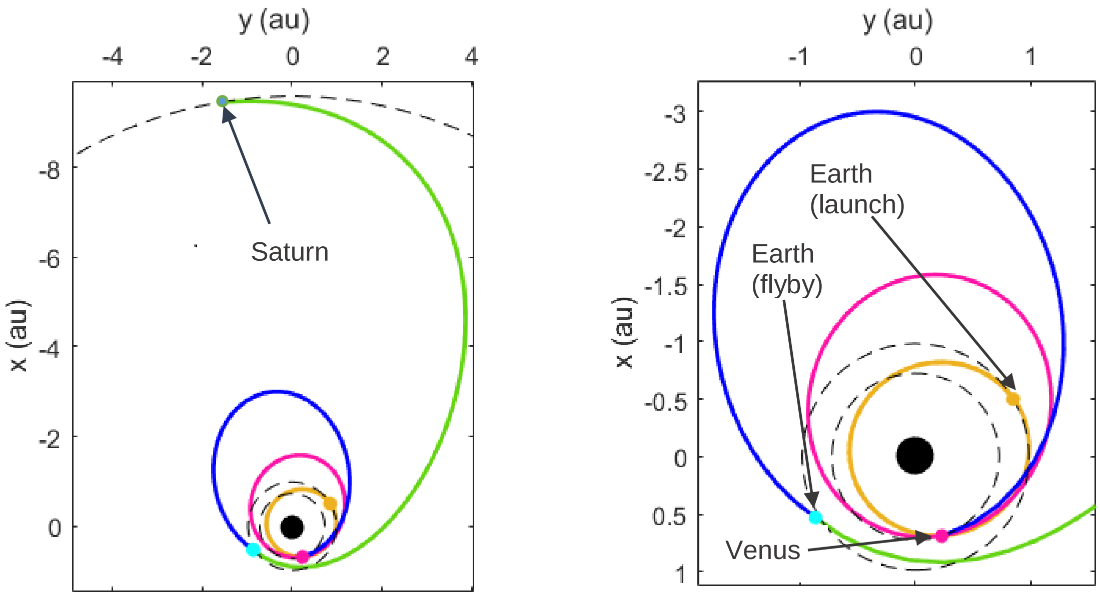


Fig. 2. The optimal EVEES trajectory (left) and the zoomed view showing the inner part (right). The dashed lines represent orbits of the planets.

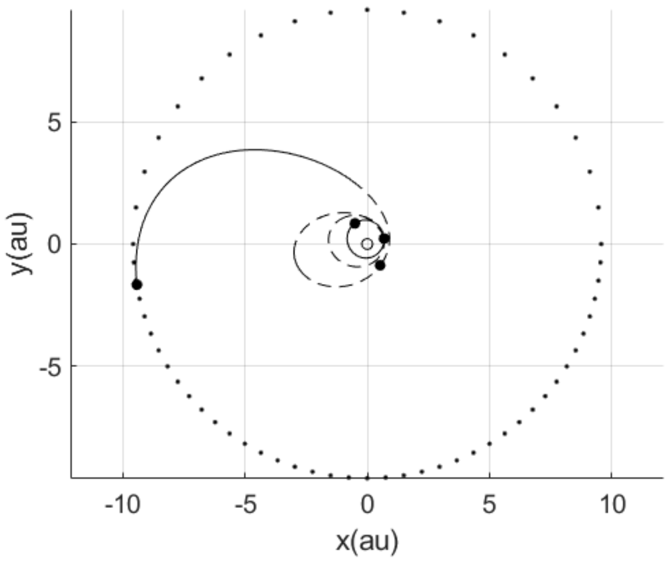


Fig. 3. Thrust (thick) and coast (dashed) arcs for the optimal EVEES trajectory. The dotted lines represent the orbit of Saturn.

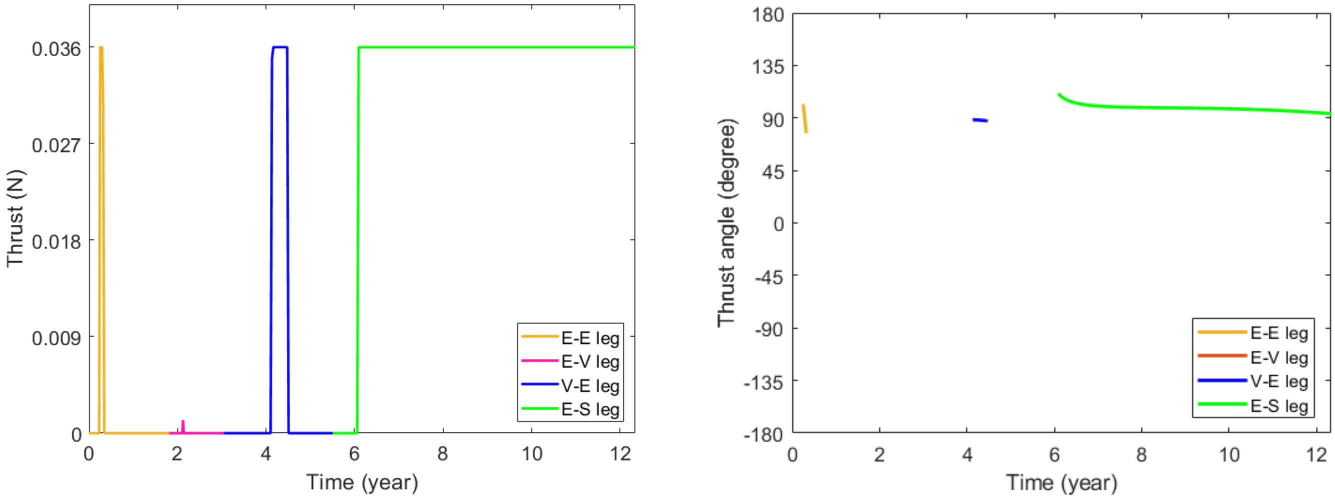


Fig. 4. Evolution of thrust magnitude (left) and thrust angle (right) for the optimal EVEES trajectory.

6. Conclusions

The objective of this contribution is to find an interplanetary trajectory to Saturn with a low arrival relative speed, to reduce substantially, or even eliminate completely, orbit insertion burns. Sequences of deep-space low-thrust arcs and gravity assist maneuvers with inner planets have been explored using a multi-objective global optimizer. The goal is to reach Saturn with an arrival hyperbolic excess speed of 1 km/s, while minimizing the launch energy and propellant consumption. Thereafter, the trajectory that best meets the mission requirements was refined with a higher fidelity direct optimization algorithm. This second stage takes as input the sequence of flybys with Venus and Earth, and uses the launch date and trajectory from the first step as initial guesses to optimize the thrust arcs, coast segments and GA manoeuvres.

With an initial spacecraft mass of 1500 kg, launch energy of 27.04 km^2/s^2, and 640 W of power for the Hall effect thruster (yielding 36 mN at an specific impulse of 1600 s) we found that it is possible to reach Saturn in 12.34 years (launch on January 21st 2028 and arrival on May 24th 2040) with an arrival mass of 1014 kg. The spacecraft departs Earth and performs two resonant gravity assist manoeuvres with Venus, followed by one Earth flyby, before arriving at Saturn (Earth-Venus-Venus-Earth-Saturn trajectory). The electrical power assumed for the calculations can be supplied by radioisotope thermoelectric generators, avoiding the issues arising from reduced solar radiation in the outer planets. The low relative approach velocity allows unpowered orbit insertion by means of a GA with Titan, enabling an eventual in-depth exploration tour of the inner large moons (i.e., Dione, Tethys, Enceladus and Mimas).

Acknowledgements

The authors are very grateful to Dr. David Morante for his assistance on the use of the global trajectory optimizer. The work of B. M. Burhani, R. Flores and E. Fantino has been supported by Khalifa University of Science and Technology’s internal grant CIRA-2021-65 / 8474000413. R. Flores also acknowledges financial support from the Spanish Ministry of Economy and Competitiveness “Severo Ochoa Programme for Centres of Excellence in R&D” (CEX2018-000797-S). In addition, E. Fantino received support from Khalifa University of Science and Technology’s Space and Planetary Science Center (KU-SPSC / 8474000336) and from the Spanish Ministry of Science and Innovation under projects PID2020-112576GB-C21 and PID2021-123968NB-100. M. Sanjurjo-Rivo acknowledges fund PID2020-112576GB-C22 of the Spanish Ministry of Science and Innovation.

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