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THE USE THE FLYBY FOR OPTIMAL SOLUTIONS

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Abstract: The spacecraft propulsion system has passed for diverse evolutions, leaving combustion engines and arriving at ion propulsion. The necessity of more efficient rockets stimulated the research in this scope. In this work ΔV will be analyzed proceeding from an electric propellant acting in set with gravitational maneuvers. The optimization of maneuvers will be approached in interplanetary missions using solar electric propulsion and Gravity Assisted Maneuver attended to reduce the costs of the mission. The high specific impulse of electric propulsion makes a Gravity Assisted Maneuver 1 year after departure convenient. Missions for several Near Earth Asteroids will be considered. The analysis suggests criteria for the definition of initial solutions demanded for the process of optimization of trajectories.

keywords: Astrodynamics, Celestial Mechanics, Space Trajectories, Flyby, Solar Electric Propulsion.

1. INTRODUCTION

Indirect optimization methods are suitable for the low thrust trajectories that are used in simulations. A finite force is applied during a finite interval of time and it is necessary to integrate the state equation along the time to know its effect. In this paper, theory of optimal control is applied and a procedure based on the Newton Method to decide the boundary problems is developed. The Pontryagin's Maximum Principle (PMP) is used to maximize the Hamiltonian associated to the problem and evaluates the optimal structure of the "switching function".

The spacecraft leaves the Earth's sphere of influence with a hyperbolic velocity whose optimal magnitude and the direction will be supplied by the optimization procedure. The initial mass is directly related to the magnitude of the hyperbolic velocity, assuming that a chemical thruster is used to leave a low Earth orbit (LEO). Out of the Earth's sphere of influence, the electric propellants is activate and the available power is proportional to the square of the distance from the sun; the propulsion is provided by one or two "PPS 1350 ion thrusters and Phall1 thrusters (UNB)".

2. OPTIMIZATION PROCEDURES

The objective is to use the theory of optimal control to maximize the spacecraft final mass.
Dynamical equations are,

$$
\begin{aligned}
&\dot{\vec{r}} = \vec{v} \\
&\dot{\vec{v}} = \vec{g}(\vec{r}) + \frac{\vec{T}}{m} \\
&\dot{m} = -\frac{\vec{T}}{c}
\end{aligned}
\qquad (1)
$$

Applying the theory of optimal control, the Hamiltonian function is defined as [1]:

$$H = \vec{\lambda}_r^t \vec{v} + \vec{\lambda}_v^t (\vec{g} + \frac{\vec{T}}{m}) - \lambda_m \frac{\vec{T}}{c} \qquad (2)$$

An indirect optimization procedure is used to maximize the payload. According to Pontryagin's Maximum Principle the optimal controls maximize H.
The nominal thrust T_o at 1 AU, and the electrical power are [1],

$$
\begin{aligned}
&P_0 = \frac{T_0 c}{2\eta} \\
&T_{Max} = \frac{T_0}{r^2}
\end{aligned}
\qquad (3)
$$

Optimal control theory provides differential equation for the adjoint equations of the problem (Euler-Lagrange).

3. MISSION ASTEROID 1989UQ

The following types of missions had been simulated:

1. without flyby;
2. Earth Gravity Assisted - EGA mission
3. Earth and Venus Gravity Assisted - EVGA mission

Using the optimization procedure we can find optimal trajectories, with the maximization of the spacecraft final mass (i.é., minimum fuel consumption). These trajectories depend on the mission objectives, for example, the performance depends on the mission time length. It is possible to reduce the time with some more spend of propellant.

3.1 ANALYSIS WITH PPS1350 (ESA)

The necessary optimal condition were formulated in agreement with the problem; the bang-bang control was used in the formulization with limited power and constraint in the time of flight.

Table 1 – Simulation with PPS 1350 (ESA)

Asteroid 1989UQ				
PPS 1350 (I_s= 1550s) (2 x 70mN)				
Duration ΔT (days)	**Δm (% m_0)**	***Data***	**ΔV_{el} (Electric) (km/s)**	**V_∞ (km/s)**
Flyby: 0				
893.48	**76.52%**	**Departure: 01/10/2017 Arrival: 13/03/2020**	**4.06805051**	**1.25579628**
***Flyby: 1* – Earth (EGA)**				
920.09	**84.94%**	**Departure: 11/07/2025 EGA 30/09/2026 Arrival: 17/01/2028**	**2.481256546**	**0.800492443**
***Flyby*: 2 - Earth – Venus (EVGA)**				
1164.92	**87.92%**	**Departure: 25/06/2017 EGA 19/09/2018 EVGA 05/03/2019 Arrival: 02/09/2020**	**1.956977088**	**0.694198512**
m_0 = 2133,3kg, Δm = *optimal mass useful*				

3.2 ANALYSIS WITH PHALL 1 (UNB)

The researchers of the Plasma Laboratory of the Physics Institute of the Brasilia University (UNB), since 2002, pledge in the study and development of a propellant that uses a plasma propulsion system produced by current Hall, based on Stationary Plasma Thrusters (SPT). Been verified resulted better in comparison to the results gotten with PPS 1350 (Table 2 and 3), therefore, Phall 1 possess a bigger specific thrust and the thruster (T) is bigger in magnitude.

Table 2 - Simulation with Phall

Asteroid 1989UQ				
PHall (UNB) (Is= 1607s) (2 x 126mN)				
Duration ΔT (days)	**Δm (% m_0)**	***Data***	**ΔV_{el} (Electric) (km/s)**	**V_∞ (km/s)**
Flyby: 0				
1305.5	**78.22%**	**Departure: 01/10/2017 Arrival: 29/04/2021**	**3.870516065**	**0.9860237**
***Flyby: 1* – Earth (EGA)**				
567.62	**82.44%**	**Departure: 11/08/2024 *EGA* 10/11/2025 Arrival: 02/03/2026**	**3.04349697**	**0.8444077**
***Flyby: 2* - Earth – Venus (EVGA)**				
1096.3	**91.77%**	**Departure: 16/06/2017 EGA 20/09/2018 EVGA 06/03/2019 Arrival: 16/06/2020**	**1.353277282**	**0.7488915**
m_0 = 2133,3kg, Δm = *optimal mass useful*				

The present analysis favor a guess at the tentative solution as the Earth's positions as departure and flyby are a priori known. The ideal asteroid has perihelion radius which is close to 1AU, a low-energy orbit and low inclination with relation to the ecliptic plane.

4. CONCLUSION

Indirect optimization methods based on optimal control theory supply accurate solutions. The use of Gravity Assisted Maneuver (EGA, EMGA or EVGA) in this mission reduces the fuel consumption and the time of the maneuver, demonstrating that this important formulation is viable and useful.

Orbits with Phall 1 had been analyzed using gravity assisted maneuvers and verified resulted optimistically for the implantation of probes using this technology, also being able to use this formularization in the future missions that use launch vehicle that is in development/improvement (VLS-2, Brazil), which can inject in LEO (low earth orbit) a satellite medium sized, thereafter, use the solar electric propulsion (SEP) or nuclear (NEP) to dislocate the vehicle for desired orbits, maximizing them with the maneuver that use assisted gravity.

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REFERENCES

[1] SANTOS, D. P. S. **Otimização de trajetórias espaciais com propulsão elétrica solar e manobras gravitacionalmente assistidas**. 2009. 128 p. (INPE-16618-TDI/1594). Tese (Doutorado em Mecânica Espacial e Controle) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos. 2009. Disponível em: <http://urlib.net/sid.inpe.br/mtc-m18@80/2009/10.06.12.40>.