

Avoiding Collisions Maneuvers Using a Stochastic Approach

Vivian Martins Gomes and Antonio F. B. A. Prado

Abstract - The research considered here is related to the problem of orbital maneuvers. A satellite has to perform such maneuver to escape from a possible collision with a cloud of particles. To perform this task, a low thrust control is available. The question of minimizing the fuel consumption is considered and this is the most important goal in the maneuver. For this problem, the hybrid optimal control approach is used, where it is possible to take into account the accuracy in the satisfaction of the constraints. The spacecraft is considered to be traveling in Keplerian orbits perturbed only by the thrusts. These thrusts have a fixed magnitude and operating in an on-off mode. Several results are shown to exemplify the maneuvers simulated.

Key-Words- Astrodynamics, artificial satellites, orbital dynamics, swing-by, transfer orbits.

I. INTRODUCTION

The main idea explored in the present paper is to study the orbital maneuvers required by a spacecraft that needs to escape from a potential collision with a cloud of debris that was generated by an explosion of another satellite. It is assumed that the orbit of the satellite is given, as well as a nominal orbit for this satellite that allows it to escape from the described collision. This risk of collision is calculated based in the propagation of a cloud of particles that perform a close approach with a celestial body. Then, this passage generates a set of new orbital elements. With this information, it is possible to obtain a set of Keplerian elements that specify an orbit that is safe, regarding this possible collision.

Then, it is necessary to maneuver this satellite from its current position to the nominal safe specified orbit, and then back to its original orbit after the cloud of particles complete its motion near the orbit of the spacecraft.

The control available to perform this maneuver is the application of a low thrust to the satellite and the objective is to perform this maneuver with minimum fuel consumption.

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An optimal approach will be used, to allow the maximum possible savings. There is no time restriction involved here and the spacecraft can leave from any point in the initial orbit. In the present paper, the stochastic version of the projection of the gradient method is used. This version allows us to include the fact that the constraints do not need to be exactly satisfied (see reference [1] and [2]). This is done to realistically treat the numerical inaccuracies and/or flexibility in terms of tolerance in mission requirements, leading to situations where the final state is constrained to lie inside a given region, instead of having an exact value.

II. REVIEW OF ORBITAL MANEUVERS

One of the most important works done in this field is the one made by Hohmann [3]. He solved the problem of minimum ΔV transfers between two circular coplanar orbits. The Hohmann transfer would be generalized to the elliptic case (transfer between two coaxial elliptic orbits) by Marchal [4].

Smith [5] shows results for some other special cases, like coaxial and quasi-coaxial elliptic orbits, circular-elliptic orbits, two quasi-circular orbits. A numerical scheme to solve the transfer between two generic coplanar elliptic orbits is presented by Bender [6].

Another line of research studies the effects of the finite thrust, like the one used in the present paper, in the results obtained from the impulsive model. Zee [7] obtained analytical expressions for the extra fuel consumed to reach the same transfer and for the errors in the orbital elements and energy for a nominal maneuver (a real maneuver that uses the impulses calculated with the impulsive model).

Later, the literature studied the problem of a two-impulse transfer where the magnitude of the two impulses are fixed, like in Jin and Melton [8]; Jezewski and Mittleman [9].

The three-impulse concept was introduced in the literature by Hoelker and Silber [10] and Sthernfeld [11]. They showed that a bi-elliptical transfer between two circular orbits has a lower ΔV than the Hohmann transfer, for some combinations of initial and final orbits. After that, Ting [12] showed that the use of more than three

impulses does not lower the ΔV , for impulsive maneuvers. Roth [13] obtained the minimum ΔV solution for a bi-elliptical transfer between two inclined orbits. Following the idea of more than two impulses, we have the work done by Prussing [14] that admits two or three impulses; Prussing [15] that admits four impulses; Eckel [16] that admits N impulses.

Some other researchers worked on methods where the number of impulses is a free parameter, and not a value fixed in advance. It is the case of the papers made by Lion and Handelsman [17], Jezewski and Rosendaal [18], Gross and Prussing [19], Eckel [20] and Prussing and Chiu [21]. Most of the research done in this particular case is based on the "Primer-Vector" theory developed by Lawden [22], [23].

Another feature that was introduced in the orbital maneuvers is the concept of a swing-by. This is a technique that uses a close approach between the spacecraft and a celestial body to increase or decrease the energy of the spacecraft. References [24] to [27] describe this problem in more details.

III. DEFINITION OF THE PROBLEM

The basic problem discussed in this paper is the problem of orbit transfer maneuvers. The objective of this problem is to modify the orbit of a given spacecraft. In the case considered in this paper, an initial and a final orbit around the Earth are completely specified. The problem is to find how to transfer the spacecraft between those two orbits in such way that the fuel consumed is minimum. There is no time restriction involved here and the spacecraft can leave and arrive at any point in the given initial and final orbits. The maneuver is performed with the use of an engine that is able to deliver a thrust with constant magnitude and variable direction. The mechanism, time and fuel consumption to change the direction of the thrust is not considered in this paper.

IV. MODEL USED

The spacecraft is supposed to be in Keplerian motion controlled only by the thrusts, whenever they are active. This means that there are two types of motion:

i) A Keplerian orbit that is an orbit obtained by assuming that the Earth's gravity (assumed to be a point of mass) is the only force acting on the spacecraft. This motion occurs when the thrusts are not firing;

ii) The motion governed by two forces: the Earth's gravity field (also assumed to be a point of mass) and the force

delivered by the thrusts. This motion occurs during the time that the thrusts are firing.

The thrusts are assumed to have the following characteristics:

i) Fixed magnitude: The force generated by them is always of constant magnitude during the maneuver. The value of this constant is a free parameter (an input for the algorithm developed here) that can be high or low;

ii) Constant Ejection Velocity: Meaning that the velocity of the gases ejected from the thrusts is constant;

iii) Free angular motion: This means that the direction of the force given by the thrusts can be modified during the transfer. This direction can be specified by the control angles $u_1 = \alpha$ and $u_2 = \beta$, called pitch (the angle between the direction of the thrust and the perpendicular to the line Earth-spacecraft) and yaw (the angle with respect to the orbital plane);

iv) Operation in on-off mode: It means that intermediate states are not allowed. The thrusts are either at zero or maximum level all the time.

Several numbers of "thrusting arcs" (arcs with the thrusts active) are tested for each maneuver. Instead of time, the "range angle" (the angle between the radius vector of the spacecraft and an arbitrary reference line in the orbital plane) is used as the independent variable, as used by Biggs [28], [29]. Figures 1 shows this situation.

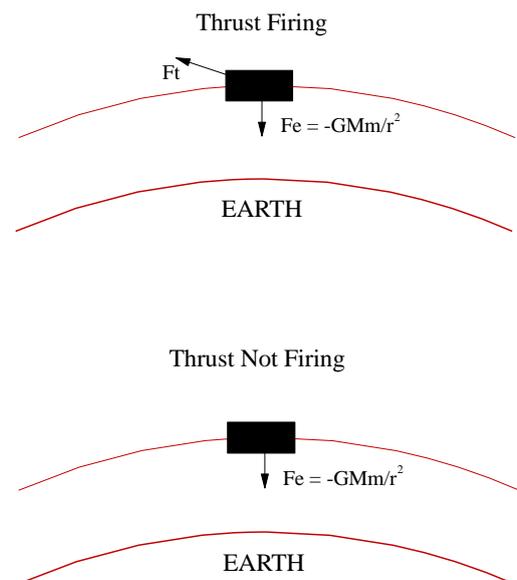


Fig. 1: Types of motion

V. OPTIMAL CONTROL FORMULATION

The minimum fuel spacecraft maneuver can be treated as a typical optimal control problem, formulated as follows.

Objective Function: Let M_f , the final mass of the vehicle, to be maximized with respect to the control $\underline{u}(\cdot)$;

Subject to:

$$\dot{\underline{x}} = \underline{f}(\underline{x}, \underline{u}, s); \tag{1}$$

$$\underline{C_e}(\underline{x}, \underline{u}, s) = \underline{E_e}; \tag{2}$$

$$\underline{C_d}(\underline{x}, \underline{u}, s) \leq \underline{E_d}; \tag{3}$$

$$\underline{h}(\underline{x}(t_f), t_f) = \underline{E_h}, t_0 \text{ and } \underline{x}(t_0) \text{ given} \tag{4}$$

where \underline{x} is the state vector, $\underline{f}(\cdot)$ is the right hand side of equations of motion, as in Biggs [29] and Prado and Rios-Neto [30]; s is the independent variable ($s_0 \leq s \leq s_f$), $\underline{C_e}(\cdot)$ and $\underline{C_d}(\cdot)$ are the algebraic dynamic constraints on state and control of dimensions m_e and m_d ; $\underline{h}(\cdot)$ are the boundary constraints of dimension m_h ; and $\underline{E_e}$, $\underline{E_d}$, $\underline{E_h}$ error vectors satisfying:

$$|\underline{E_e}_i| \leq \underline{E_e}_i^T, i = 1, 2, 3, \dots, m_e \tag{5}$$

$$|\underline{E_d}_i| \leq \underline{E_d}_i^T, i = 1, 2, 3, \dots, m_d \tag{6}$$

$$|\underline{E_h}_i| \leq \underline{E_h}_i^T, i = 1, 2, 3, \dots, m_h \tag{7}$$

where the fixed given values $\underline{E_e}_i^T$, $\underline{E_d}_i^T$, $\underline{E_h}_i^T$, characterizes the region around zero within which errors are considered tolerable.

To avoid singularities problems, we use the following variables.

$$X_1 = [a \cdot (1 - e^2) / \mu]^{1/2} \tag{8}$$

$$X_2 = e \cdot \cos(\omega - \phi) \tag{9}$$

$$X_3 = e \cdot \sin(\omega - \phi) \tag{10}$$

$$X_4 = (\text{Fuel Consumed}) / m_0 \tag{11}$$

$$X_5 = t \tag{12}$$

$$X_6 = \cos(i/2) \cdot \cos((\Omega + \phi)/2) \tag{13}$$

$$X_7 = \sin(i/2) \cdot \cos((\Omega - \phi)/2) \tag{14}$$

$$X_8 = \sin(i/2) \cdot \sin((\Omega - \phi)/2) \tag{15}$$

$$X_9 = \cos(i/2) \cdot \sin((\Omega + \phi)/2) \tag{16}$$

where:

a = semi-major axis;

e = eccentricity;

i = inclination;

Ω = argument of the ascending node;

ω = argument of perigee;

f = true anomaly;

s = range angle;

$$\phi = f + \omega - s; \tag{17}$$

μ = gravitational constant;

m_0 = initial mass of the spacecraft.

Using those variables we can study planar and circular orbits without any problem in terms of singularities. In those new variables, the equations of motion are shown below.

$$dX_1/ds = f_1 = Si \cdot X_1 \cdot F_1 \tag{18}$$

$$dX_2/ds = f_2 = Si \cdot \{[(Ga+1) \cdot \cos(s) + X_2] \cdot F_1 + v \cdot F_2 \cdot \sin(s)\} \tag{19}$$

$$dX_3/ds = f_3 = Si \cdot \{[(Ga+1) \cdot \sin(s) + X_3] \cdot F_1 - v \cdot F_2 \cdot \cos(s)\} \tag{20}$$

$$dX_4/ds = f_4 = Si \cdot f \cdot F \cdot (1 - X_4) / (X_1 \cdot W) \tag{21}$$

$$dX_5/ds = f_5 = Si \cdot f \cdot (1 - X_4) \cdot m_0 / X_1 \tag{22}$$

$$dX_6/ds = f_6 = - Si \cdot F_3 \cdot [X_7 \cdot \cos(s) + X_8 \cdot \sin(s)] / 2 \tag{23}$$

$$dX_7/ds = f_7 = Si \cdot F_3 \cdot [X_6 \cdot \cos(s) - X_9 \cdot \sin(s)] / 2 \tag{24}$$

$$dX_8/ds = f_8 = Si \cdot F_3 \cdot [X_9 \cdot \cos(s) + X_6 \cdot \sin(s)] / 2 \tag{25}$$

$$dX_9/ds = f_9 = Si \cdot F_3 \cdot [X_7 \cdot \sin(s) - X_8 \cdot \cos(s)] / 2 \tag{26}$$

where:

$$Ga = 1 + X_2 \cdot \cos(s) + X_3 \cdot \sin(s) \tag{27}$$

$$Si = (\mu \cdot X_1^4) / [Ga^3 \cdot m_0 \cdot (1 - X_4)] \tag{28}$$

Where F , F_1 , F_2 , F_3 are the forces generated by the thrust and they are given by:

$$\vec{F} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 \quad (29)$$

$$|\vec{F}| = F \quad (30)$$

$$F_1 = F \cdot \cos(\alpha) \cdot \cos(\beta) \quad (31)$$

$$F_2 = F \cdot \sin(\alpha) \cdot \cos(\beta) \quad (32)$$

$$F_3 = F \cdot \sin(\beta) \quad (33)$$

The equations for the Lagrange multipliers are given below.

$$\frac{dp_1}{ds} = -[4 \cdot \sum_{j=1}^9 p_j \cdot f_j + p_1 \cdot f_1 - p_4 \cdot f_4 - p_5 \cdot f_5] / X_4 \quad (34)$$

$$\frac{dp_2}{ds} = \frac{\cos(s)}{Ga} \cdot [3 \cdot \sum_{j=1}^9 p_j \cdot f_j - p_4 \cdot f_4 - p_5 \cdot f_5] - S_i \cdot p_2 \cdot F_1 - S_i \cdot \cos^2(s) \cdot (p_2 \cdot F_1 - p_3 \cdot F_2) - S_i \cdot \cos(s) \cdot \sin(s) \cdot (p_2 \cdot F_2 + p_3 \cdot F_1) \quad (35)$$

$$\frac{dp_3}{ds} = \frac{\sin(s)}{Ga} \cdot [3 \cdot \sum_{j=1}^9 p_j \cdot f_j - p_4 \cdot f_4 - p_5 \cdot f_5] - S_i \cdot p_3 \cdot F_1 - S_i \cdot \cos(s) \cdot \sin(s) \cdot (p_2 \cdot F_1 - p_3 \cdot F_2) - S_i \cdot \sin^2(s) \cdot (p_2 \cdot F_2 + p_3 \cdot F_1) \quad (36)$$

$$\frac{dp_4}{ds} = -[\sum_{j=1}^9 p_j \cdot f_j - p_4 \cdot f_4 - p_5 \cdot f_5] / [m_0 \cdot (1 - X_4)] \quad (37)$$

$$\frac{dp_5}{ds} = 0 \quad (38)$$

$$\frac{dp_6}{ds} = -S_i \cdot F_3 \cdot [p_7 \cdot \cos(s) + p_8 \cdot \sin(s)] / 2 \quad (39)$$

$$\frac{dp_7}{ds} = S_i \cdot F_3 \cdot [p_6 \cdot \cos(s) - p_9 \cdot \sin(s)] / 2 \quad (40)$$

$$\frac{dp_8}{ds} = S_i \cdot F_3 \cdot [p_6 \cdot \sin(s) + p_9 \cdot \cos(s)] / 2 \quad (41)$$

$$\frac{dp_9}{ds} = -S_i \cdot F_3 \cdot [p_8 \cdot \cos(s) - p_7 \cdot \sin(s)] / 2 \quad (42)$$

The control to be applied to the spacecraft also needs a transformation in order to avoid numerical problems. Then, we use the following set of variables.

$$u_1 = s_0 \quad (43)$$

$$u_2 = (s_f - s_0) \cdot \cos(\beta_0) \cdot \cos(\alpha_0) \quad (44)$$

$$u_3 = (s_f - s_0) \cdot \cos(\beta_0) \cdot \sin(\alpha_0) \quad (45)$$

$$u_4 = (s_f - s_0) \cdot \sin(\beta_0) \quad (46)$$

$$u_5 = \alpha' \quad (47)$$

$$u_6 = \beta' \quad (48)$$

The optimal control can be obtained at every instant of time by extremizing the Hamiltonian of the system. This is an application of the first order necessary conditions of the optimal problem. The equations that represent this fact are given below.

$$\sin(\alpha) = q_2 / S' \quad (49)$$

$$\sin(\beta) = q_3 / S'' \quad (50)$$

$$\cos(\alpha) = q_1 / S' \quad (51)$$

$$\cos(\beta) = S' / S'' \quad (52)$$

where:

$$S' = \pm [q_1^2 + q_2^2]^{1/2} \quad (53)$$

$$S'' = \pm [q_1^2 + q_2^2 + q_3^2]^{1/2} \quad (54)$$

$$q_1 = p_1 \cdot X_1 + p_2 \cdot [X_2 + (Ga + 1) \cdot \cos(s)] + p_3 \cdot [X_3 + (Ga + 1) \cdot \sin(s)] \quad (55)$$

$$q_2 = p_2 \cdot Ga \cdot \sin(s) - p_3 \cdot Ga \cdot \cos(s) \quad (56)$$

$$q_3 = - \{ p_6 \cdot [X_7 \cdot \cos(s) + X_8 \cdot \sin(s)] + p_7 \cdot [X_6 \cdot \cos(s) - X_9 \cdot \sin(s)] + p_8 \cdot [X_6 \cdot \sin(s) + X_9 \cdot \cos(s)] + p_9 \cdot [X_7 \cdot \sin(s) - X_8 \cdot \cos(s)] \} / 2 \quad (57)$$

There are several constraints that can be considered in

this type of problem. They can be represented by the equations shown below.

$$S(\cdot) \geq 0 \tag{58}$$

$$\frac{(a - a^*)}{|a_0 - a^*|} = 0 \tag{59}$$

$$\frac{[a(1+e) - a^*(1+e^*)]}{|a_0(1+e_0) - a^*(1+e^*)|} = 0 \tag{60}$$

$$\frac{(i - i^*)}{|i_0 - i^*|} = 0 \tag{61}$$

$$\frac{(\Omega - \Omega^*)}{|\Omega_0 - \Omega^*|} = 0 \tag{62}$$

$$\frac{(\omega - \omega^*)}{|\omega_0 - \omega^*|} = 0 \tag{63}$$

Figure 2 shows some of the variables used to describe this problem.

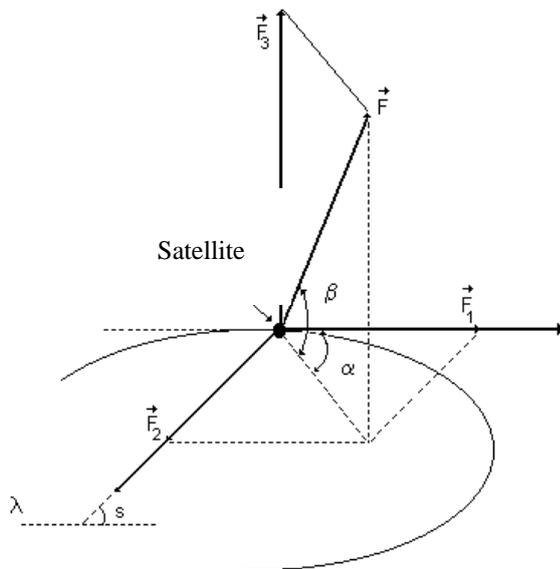


Fig. 2 - Variables of the system

VI. MATHEMATICAL METHOD

This approach is based on Optimal Control Theory (Bryson [31]). First order necessary conditions for a local

minimum are used to obtain the adjoint equations and the Pontryagin's Maximum Principle to obtain the control angles at each range angle, leading to a "Two Point Boundary Value Problem" (TPBVP), where the difficulty is to find the initial values of the Lagrange multipliers. The treatment given here [29] is the hybrid approach of guessing a set of values, integrating numerically all the differential equations and then searching for a new set of values, based on a nonlinear programming algorithm. With this approach, the problem is again reduced to parametric optimization, as in the suboptimal method, with the difference that the angles' parameters are replaced by the initial values of the Lagrange multipliers, as variables to be optimized.

The method showed by Biggs [29] was used, where the "adjoint-control" transformation is performed and, instead of the initial values of Lagrange multipliers, one guesses control angles and their rates at the beginning of thrusting. With this, it is easier to find a good initial guess, and the convergence is faster. This hybrid approach has the advantage that, since the Lagrange multipliers remain constant during the "ballistic arcs", it is necessary to guess values of the control angles and its rates only for the first "burning arc". This transformation reduces very much the number of variables to be optimized and, as a consequence, the time of convergence.

VII. NUMERICAL METHOD

To solve the nonlinear programming problem, the stochastic version of the projection of the gradient method (Rios-Neto and Pinto [1]) was used.

Its general scheme is resumed in what follows:

Given a value $\bar{\underline{p}}$ of the searched vector of parameters \underline{p} , from an initial guess or from an immediately previous iteration, a first order, direct search approach is adopted in a typical iteration to determine an approximate solution for the increment $\Delta \underline{p}$ in the problem:

$$\text{Minimize: } J(\bar{\underline{p}} + \Delta \underline{p}) \tag{64}$$

$$\text{Subject to: } \underline{C_e}(\bar{\underline{p}} + \Delta \underline{p}) = \alpha \underline{C_e}(\bar{\underline{p}}) + \underline{Ee} \tag{65}$$

$$\underline{C_d}(\bar{\underline{p}} + \Delta \underline{p}) = \beta \underline{C_d}(\bar{\underline{p}}) + \underline{Ed} \tag{66}$$

where $J(\underline{p})$ is the objective function; $\underline{C_e}(\underline{p})$ the equality constraints; $\underline{C_d}(\underline{p})$ the active inequality constraints at \underline{p} ; and $0 \leq \alpha < 1$, $0 \leq \beta < 1$ are chosen close enough to one to lead to increments $\Delta \underline{p}$ of a first order of magnitude.

Linearized approximations are taken for the left hand

sides of Equations (65) and (66) together with a stochastic interpretation for the errors \underline{Ee} and \underline{Ed} , resulting in:

$$(\alpha - 1)\underline{Ce}(\underline{\bar{p}}) = (d[\underline{Ce}(\underline{\bar{p}})]/d\underline{p}) \Delta\underline{p} + \underline{Ee} \quad (67)$$

$$(\beta - 1)\underline{Cd}(\underline{\bar{p}}) = (d[\underline{Cd}(\underline{\bar{p}})]/d\underline{p}) \Delta\underline{p} + \underline{Ed} \quad (68)$$

where \underline{Ed} and \underline{Ee} are now assumed to be zero mean uniformly distributed errors, modeled as:

$$E[\underline{EeEe}^T] = \text{diag} [e_i, i = 1, 2, \dots, m_e]$$

$$E[\underline{EdEd}^T] = \text{diag} [d_i, i = 1, 2, \dots, m_d]$$

where $E[\cdot]$ indicate the expected value of its argument.

The condition of Equation (64) is approximated by the following "a priori information":

$$-g \cdot \underline{\nabla} J^T(\underline{\bar{p}}) = \Delta\underline{p} + \underline{n} \quad (69)$$

where $g \geq 0$ is to be adjusted to guarantee a first order of magnitude for the increment, that is, such that $\Delta\underline{p}$ is small enough to permit the use of a linearized representation of $J(\underline{\bar{p}} + \Delta\underline{p})$; and \underline{n} is taken as a zero mean uniformly distributed random vector, modelling the a priori searching error in the direction of the gradient $\underline{\nabla} J(\underline{\bar{p}})$, with:

$$E[\underline{nn}^T] = \underline{\bar{P}} \quad (70)$$

as its diagonal covariance matrix. The values of the variances in $\underline{\bar{P}}$ are chosen such as to characterize an "adequate order of magnitude" for the dispersion of \underline{n} . The diagonal form adopted is to model the assumption that it is not imposed any a priori correlation between the errors in the gradient components.

The simultaneous consideration of conditions of Equations (67), (68) and (69) characterize a problem of parameter estimation, which in a compact notation can be put as follows:

$$\underline{\bar{U}} = \underline{U} + \underline{n} \quad (71)$$

$$\underline{Y} = \underline{M}\underline{U} + \underline{V} \quad (72)$$

where $\underline{\bar{U}} \triangleq -g \cdot \underline{\nabla} J^T(\underline{\bar{p}})$ is the "a priori information";

$$\underline{U} \triangleq \Delta\underline{p};$$

$\underline{Y} \triangleq [(\alpha - 1)\underline{Ce}^T(\underline{\bar{p}}) : (\beta - 1)\underline{Cd}^T(\underline{\bar{p}})]$ is the observation vector;

$$\underline{M}^T \triangleq [(d[\underline{Ce}(\underline{\bar{p}})]/d\underline{p})^T : (d[\underline{Cd}(\underline{\bar{p}})]/d\underline{p})^T]; \underline{V}^T = [\underline{Ee}^T : \underline{Ed}^T].$$

Adopting a criterion of linear, minimum variance estimation, the optimal search increment can be determined using the classical Gauss-Markov estimator, which in Kalman form (e. g. Jazwinski [32]) gives:

$$\underline{\hat{U}} = \underline{\bar{U}} + \underline{K}(\underline{Y} - \underline{M}\underline{\bar{U}}) \quad (73)$$

$$\underline{P} = \underline{\bar{P}} - \underline{K}\underline{M}\underline{\bar{P}} \quad (74)$$

$$\underline{K} = \underline{\bar{P}}\underline{M}^T(\underline{M}\underline{\bar{P}}\underline{M}^T + \underline{R})^{-1} \quad (75)$$

where $\underline{\bar{P}}$ is defined as before; $\underline{R} \triangleq E[\underline{VV}^T] = \text{diag} [R_k, k = 1, 2, \dots, m_e + m_d]$; and \underline{P} has the meaning of being the covariance matrix of the errors in the components estimates of \underline{U} , i. e.:

$$\underline{P} = E[(\underline{U} - \underline{\hat{U}})(\underline{U} - \underline{\hat{U}})^T] \quad (76)$$

To build a numerical algorithm using the proposed procedure, the following types of iterations are considered:

(i) Initial phase of acquisition of constraints, when starting from a feasible point that satisfies the inequality constraints, the search is done to capture the equality constraints, including those inequality constraints that eventually became active along this phase;

(ii) Search of the minimum, when from a point that satisfies the constraints in the limits of the tolerable errors \underline{V} , the search is done to take the objective function (Equation (64)) to get closer to the minimum; this search is conducted relaxing the order of magnitude of the error bounds around the constraints;

(iii) Restoration of the constraints, when from a point that resulted from a type (ii) iteration, the search is done to restore constraints satisfaction, within the limits imposed by the error \underline{V} .

Rios-Neto and Pinto [1] suggest how to choose good values for the numerical parameters that must be different for each type of iteration.

VIII. SIMULATIONS AND NUMERICAL TESTS

To verify the algorithm proposed, two maneuvers of orbit transfer was simulated. These results were compared with the ones obtained by the deterministic version, without flexibility in the constraint's satisfaction. Similar simulations can be found in references [33] and [34]. This transfer phase will occur with the data given in Table 1. Some other information are: Initial mass: 170 kg; Thrust: 4.0 N.

Table 1 - Data for Transfer Phase of the Satellite

Orbits	Initial	Final
Semi-major axis	6800.00	7050.00
Eccentricity	0.006	0.000
Inclination (degrees)	10.00	10.00
Ascending Node (degrees)	20.00	Free
Argument of perigee (degrees)	0.00	Free
Mean Anomaly (degrees)	0.00	Free

Table 2 - Errors Allowed for Final Keplerian Elements

Semi-major axis	4.0 Km
Eccentricity	0.0005
Inclination	0.01 deg

The choice of the number of "burning arcs" was done for several different values.

The consumptions found are showed in Table 3, as well as comparisons with deterministic methods.

Table 3 - Fuel Expenditure Comparisons (kg)

Approach	Stochastic	Deterministic
2 Arcs	13.77	13.98
3 Arcs	13.60	13.74
4 Arcs	13.14	13.24
5 Arcs	12.90	12.98
6 Arcs	12.49	12.55
7 Arcs	12.10	12.15
8 Arcs	11.92	11.96

Then, a new maneuver is simulated. A smaller amplitude case is used, to simulate a short orbital correction. This maneuver will occur with the data given in Table 4. The same satellite used in the previous case is used again, so the initial mass is 170 kg and the thrust level is 4.0 N.

Table 4 - Data for Orbital Correction Phase of the Satellite

Orbits	Initial	Final
Semi-major axis	7000.00	7050.00
Eccentricity	0.001	0.000
Inclination (degrees)	10.00	10.00
Ascending Node (degrees)	20.00	Free
Argument of perigee (degrees)	0.00	Free
Mean Anomaly (degrees)	0.00	Free

Table 5 - Errors Allowed for Final Keplerian Elements of the Second Maneuver

Semi-major axis	3.0 Km
Eccentricity	0.0003
Inclination	0.01 deg

The choice of the number of "burning arcs" was done for several different values.

The consumptions found are showed in Table 6, as well as comparisons with deterministic methods.

Table 6 - Fuel Expenditure Comparisons (kg) for the second maneuver

Approach	Stochastic	Deterministic
2 Arcs	2.75	2.80
3 Arcs	2.72	2.74
4 Arcs	2.63	2.64
5 Arcs	2.58	2.60
6 Arcs	2.50	2.51
7 Arcs	2.42	2.43
8 Arcs	2.38	2.39

IX. CONCLUSIONS

Optimal control was explored to generate an algorithm to obtain solutions for the problem of minimum fuel consumption to make orbital maneuvers of a satellite that needs to perform this maneuver to avoid the risk of a collision with a cloud of particles.

This problem was considered taking into account the accuracy tolerance in the constraint's satisfaction using the new nonlinear programming algorithm proposed by Rios-Neto and Pinto [1].

The results showed that some fuel can be saved by exploring tolerable errors allowed for constraint's

satisfaction. The amount saved is not negligible.

It is also possible to see that the increase of the number of burning arcs can decrease the total fuel expenditure. This happens because this increase is accompanied by an increase of the number of variables available for the optimization technique.

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REFERENCES

- [1] Rios Neto, A.; Pinto, R.L.U. A stochastic approach to generate a projection of the gradient type method. Sao Jose dos Campos, INPE, Nov. 1986 (INPE-4060-PRE/1019)
- [2] Prado, A.F.B.A.; Rios-Neto, A., "A Stochastic Approach to the Problem of Spacecraft Optimal Maneuvers". Revista Brasileira de Ciências Mecânicas, Vol. XVI, No. 3, 1994, pp. 268-278 (INPE-5192-PRE/1660).
- [3] Hohmann, W.. Die Erreichbarkeit der Himmelskorper. Oldenbourg, Munique, 1925.
- [4] Marchal, C.. Transferts optimaux entre orbites elliptiques coplanaires (Durée indifférente). Astronautica Acta, 11(6):432-445, Nov./Dec. 1965.
- [5] Smith, G.C.. The calculation of minimal orbits. Astronautical Acta, 5(5):253-265, May 1959.
- [6] Bender, D.F.. Optimum coplanar two-impulse transfers between elliptic orbits. Aerospace Engineering, 44-52, Oct. 1962.
- [7] Zee, C.H. Effect of finite thrusting time in orbital maneuvers. AIAA Journal, 1(1):60-64, Jan. 1963.
- [8] Jin, H.; Melton, R.G.. Transfers between circular orbits using fixed impulses. AAS paper 91-161. In: AAS/AIAA Spaceflight Mechanics Meeting, Houston, TX, 11-13 Feb. 1991.
- [9] Jezewski, D.J.; Mittleman, D.. An analytic approach to two-fixed-impulse transfers between Keplerian orbits. Journal of Guidance, Control, and Dynamics, 5(5):458-464, Sept./Oct. 1982.
- [10] Hoelker, R.F. and Silber, R.. The Bi-Elliptic Transfer Between Circular Co-Planar Orbits. Tech Memo 2-59, Army Ballistic Missile Agency, Redstone Arsenal, Alabama, USA.
- [11] Shternfeld, A., "Soviet Space Science," Basic Books, Inc., New York, 1959, pp. 109-111.
- [12] Ting, L. Optimum orbital transfer by several impulses. Astronautical Acta, 6(5):256-265, May 1960.
- [13] Roth, H.L.. Minimization of the velocity increment for a bi-elliptic transfer with plane change. Astronautical Acta, 13(2):119-130, May/Apr. 1967.
- [14] Prussing, J.E.. Optimal two- and three-impulse fixed-time rendezvous in the vicinity of a circular orbit. AIAA Journal, 8(7):1221-1228, July 1970.
- [15] Prussing, J.E.. Optimal four-impulse fixed-time rendezvous in the vicinity of a circular orbit. AIAA Journal, 7(5):928-935, May 1969.
- [16] Eckel, K.G.. Optimum transfer in a central force field with n impulses. Astronautica Acta, 9(5/6):302-324, Sept./Dec. 1963.
- [17] Lion, P.M.; Handelsman, M.. Primer vector on fixed-time impulsive trajectories. AIAA Journal, 6(1):127-132, Jan. 1968.
- [18] Jezewski, D.J.; Rozendaal, H.L.. An efficient method for calculating optimal free-space N-impulsive trajectories. AIAA Journal, 6(11):2160-2165, Nov. 1968.
- [19] Gross, L.R.; Prussing, J.E.. Optimal multiple-impulse direct ascent fixed-time rendezvous. AIAA Journal, 12(7):885-889, July 1974.
- [20] Eckel, K.G.. Optimal impulsive transfer with time constraint. Astronautica Acta, 9(3):139-146, May/June 1982.
- [21] Prussing, J.E.; Chiu, J.H.. Optimal multiple-impulse time-fixed rendezvous between circular orbits. Journal of Guidance, Control, and Dynamics, 9(1):17-22, Jan./Feb. 1986.
- [22] Lawden, D.F.. Minimal rocket trajectories. ARS Journal, 23(6):360-382, Nov./Dec. 1953.
- [23] Lawden, D.F.. Fundamentals of space navigation. JBIS, 13:87-101, May 1954.
- [24] Gomes, V. M.; Prado, A. F. B. A. P. "Effects of the variation of the periapsis velocity in a swing-by maneuver of a cloud of particles". Proceedings: Recent Advances in Applied and Theoretical Mechanics, p.106-108, ISBN 978-960-474-140-3, Tenerife, Spain, 2009.
- [25] Gomes, V. M.; Prado, A. F. B. A.; "A Numerical Study of the Dispersion of a Cloud of Particles" CD: Proceedings of 20th International Congress of Mechanical Engineering (COBEM), COB09-1980, ISSN 2176-5480, 2009.
- [26] Gomes, V. M.; Prado, A. F. B. A. "The Use of Gravitational Capture For Space Travel", 60th International Astronautical Congress, CD: IAC Proceedings, IAC-09-A3.2int.16, ISSN 1995-6258, Daejeon, South Korea, 2009.
- [27] Gomes, V. M.; Prado, A. F. B. A. P. "A Study of the Close Approach Between a Planet and a Cloud of Particles", Recent Advances in Signal Processing, Robotics and Automation, pg. 126-131. ISBN 978-960-474-054-3, Cambridge, England, 2009.
- [28] Biggs, M.C.B.. The Optimization of Spacecraft Orbital Manoeuvres. Part I: Linearly Varying Thrust Angles. The Hatfield Polytechnic, Numerical Optimization Centre, England, 1978.
- [29] Biggs, M.C.B. The optimisation of spacecraft orbital manoeuvres. Part II : Using Pontryagin's maximum principle. The Hatfield Polytechnic, Numerical Optimisation Centre, Jan. 1979.
- [30] Prado, A.F.B.A. & A. Rios-Neto. Suboptimal and Hybrid Numerical Solution Schemes for Orbit Transfer Maneuvers. SBA Controle & Automação, Vol. 4, no. 2, pp 82-88.
- [31] Bryson, A.E. and Ho, Y.C. Applied optimal control, Wiley, New York, 1975.
- [32] Jazwinski, A.H.. Stochastic processes and filtering theory, Academic Press, New York, 1972.
- [33] Gomes, V. M.; Prado, A. F. B. A. P.; Kuga, H. K. "Orbital maneuvers Using Low Thrust", Recent Advances in Signal Processing, Robotics and Automation, pg. 120-125. ISBN 978-960-474-054-3, Cambridge, England, 2009.

[34] Prado, A. F. B. A.; Gomes, V. M.; Fonseca, I. M. "Low thrust orbital maneuvers to insert a satellite in a constellation". Proceedings: 4th International Workshop on Satellite

Constellations and Formation Flying, Instituto Nacional de Pesquisas Espaciais, São José dos Campos – SP – Brazil, 14 – 16 February, 2005.