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ABSTRACT

In this paper we investigated the feasibility of the orbital trajectories as function of the available fuel to realize the correction maneuvers and the thruster motor power. We found small fuel consumption to in-plane maneuvers under increasing thrust vector deviations w.r.t. that to out-plane maneuvers. The correction maneuvers turned more difficult under increasing direction yaw deviations than to the direction pitch deviations. We present typical values to extra fuel consumption to realized the correction maneuvers under individual thrust vector deviations. With the superposition of the deviations, we verified that the motor capacity produces increasing of the final mean semi-major axis as function the direction deviations increasing. Proportionally, the fuel consumption increases in this process.

INTRODUCTION

The study of orbital maneuvers under operational realist conditions is very important to the technological and scientific applications. One space mission requires to attend many stages of the improvement to be feasible. The fuel consumption during the full mission requires studies of the non-ideal motor thrusters capacity. This non-ideality introduces several perturbations inside the trajectories realized by the space vehicle, because there are sources natural or non-natural deviations. Between the non-natural deviations we characterizes the thrust vector deviations. In the order of study and to model this operational problem and to attend to the many missions purposes, authors have investigated their effects in the orbital maneuvers. The low-thrust maneuvers are very important to realize the corrections arcs and, mainly, to salve fuel, reducing the missions cost. Many and substantial works has been done on low-thrust trajectories. Electrically propelled interplanetary missions too has been used by many space programs in this way. Edelbaum et all (1975a,b) wrote the code SECKSPOT to solve the transfers requiring multiple revolutions with low-thrus LEO to GEO.

Other more efficient code was developed by Irvine Technology Group (1992), the LOWTOP. But, the mathematical methods provided optimal solution to the low-thrust maneuvers by Enright et all (1991), Betts (1993) and Zondervan et all (1984), for example. Papers more recent showed many important results to particular space missions. Bauer (1992) studied the low-thrust effects on near-optimum transfers and Burton et all (1992) this problem to time-critical optimization. The electric propulsion was studied to return missions by Kawaguchi et all (1995) and was considered inappropriate for guidance of flyby missions because little time is available to guide the spacecraft, when it is close range of the target (Kawaguchi and Matsuo, 1996). The motor power limited is considered too as trajectories constraints besides the fuel consumption minimum. This problem was studied by Prussing (1992) to circular-circular transfer trajectory, by Haissing et all (1993) to transfers coplanar elliptical orbits, by Fernandes (1995) to close elliptical transfers orbits, obtaining the analytical solution with Mayer's problem and Hori's method. Prussing (1995) studied it to optimal trajectories in arbitrary gravitational field with Hill-Clohessy-Wiltshire model. Others authors has studied this problem under several aspects to attend the missions constraints. In this paper we present the numerical results of the maneuvers in and out-plane under thrust superposed directions deviations to investigate the motor power influence and in the corrections maneuvers. The important questions are: Is it possible the motor's power improves the corrections maneuvers? How this process would happen?

MANEUVERS UNDER NON-IDEAL CONTINUOUS THRUST

To investigate the feasibility of the orbital trajectories as function of the available fuel thruster motor power, we studied two continuous transfers maneuvers of the artificial satellite, the first, we call theoretical trajectory (TT), a low thrust transfer between high coplanar obits used by Biggs (1978,1979) and Prado (1989). The second, we call practical trajectory, a high thrust transfer between middle noncoplanar orbits, particularly, the first transfer of the EUTELSATII-F2 satellite, used by Kuga et alli (1991). Besides this, we introduce three conditions: 1) there are direction and magnitude thrust deviations; 2) all the transfer are minimum fuel consumption, with pitch and yaw angles as control variables and; 3) the deviations approach is probabilistic of gaussian function distribution. The problem involves only the gravitational and thrust forces. The geometric development of the coordinates systems for this problem can be found in Jesus et all (2002).

The Table 1 shows the final nominal and initial orbits for the theoretical maneuvers.

TABLE 1 – THEORETICAL ORBITS CHARACTERISTICS

INITIAL THEORETICAL ORBIT		FINAL NOMINAL THEORETICAL ORBIT	
Semi-major axis	99.000,000 km	Semi-major axis	104.000,000 km
Eccentricity	0,7	Eccentricity	0,714
Inclination	$10{,}0^0$	Inclination	$10{,}0^0$
Ascending node	$55{,}0^0$	Ascending node	$55{,}006^0$
Perigee argument	$105{,}0^0$	Perigee argument	$104{,}917^0$
True anomaly	$-105{,}0^0$	True anomaly	$21{,}213^0$
Thrust applied	1,0 N	Thrust applied	1,0 N
Fuel consumption	2,50 kg	Fuel consumption	2,448 kg

Eject velocity	2,5 km/s	Eject velocity	2,5 km/s

The Table 2 shows the final nominal and initial orbits for the practical maneuvers.

TABLE 2 – PRACTICAL ORBITS CHARACTERISTICS

INITIAL PRACTICAL ORBIT		FINAL NOMINAL PRACTICAL ORBIT	
Semi-major axis	24.387,948 km	Semi-major axis	27.373,907 km
Eccentricity	0,730044	Eccentricity	0,542
Inclination	$6,9948^0$	Inclination	$3,457^0$
Ascending node	$277,4743^0$	Ascending node	$276,265^0$
Perigee argument	$178,1326^0$	Perigee argument	$177,004^0$
True anomaly	$200,1568^0$	True anomaly	$189,210^0$
Thrust applied	407,3 N	Thrust applied	407,3 N
Fuel consumption	302,691 kg	Fuel consumption	289,986 kg
Eject velocity	3,013 km/s	Eject velocity	3,013 km/s

These final nominal orbits are the target-orbits in our simulations. We studied the keplerian elements deviations under non-ideal thrust and their feasibility for the optimum fuel missions and variables propulsion systems.

NUMERICAL SIMULATIONS – RESULTS OF THE KEPLERIAN ELEMENTS

The transfers orbits simulations were realized to 1000 runs. The pitch and yaw angles were taken as control variables such that the overall minimum fuel consumption defines each burn of the thrusters. The deviations over the thrust vector were modeled as gaussian, systematic (random-bias, R) or operational (white noise, W). The maximum direction deviation in pitch is $\Delta\alpha_{max}$ = DES2, in yaw is $\Delta\beta_{max}$=DES3 and in the thrust modulus is DES1. Jesus (1999) showed that for the non superposed DES1 deviations, there is not effect cause relation between this thrust modulus deviations and the final keplerian elements of the both transfers obits**.** In the Figures 1 and 2, we show the numerical results of the final mean semi-major axis (**a**) and the fuel consumption (**C**) for the final theoretical orbit and final practical orbit, respectively. In these simulations we choose some deviations combination to consider the several ranges between the strong and small thrust deviations. We pretend analyze how much efficient is the effect of these deviations sources over the final orbits and over their fuel consumption and the change of the power thrusters. In these simulations we considered systematic deviations.

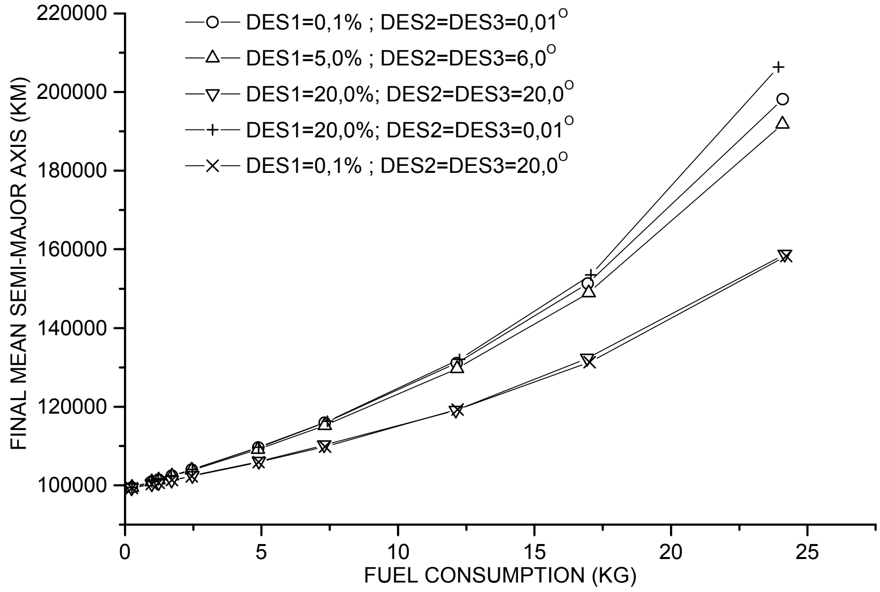

Figure 1 – Final Mean Semi-major axis vs. Fuel Consumption , TOR

This Figure 1 shows the consumption curve for the theoretical orbit under systematic and superposed deviations. We can observe in their behavior that the consumption increasing provides the satellite to obtain orbits with semi-major axis higher and these effect is reduced with the direction superposed deviations (DES2 and DES3). The effect of the DES1 deviation is not observed in any case, the small or strong DES1. This shows that the non ideal thrusters systems requires more fuel consumption to reach final mean semi-major axis w.r.t. the equivalent ideal thrusters systems.

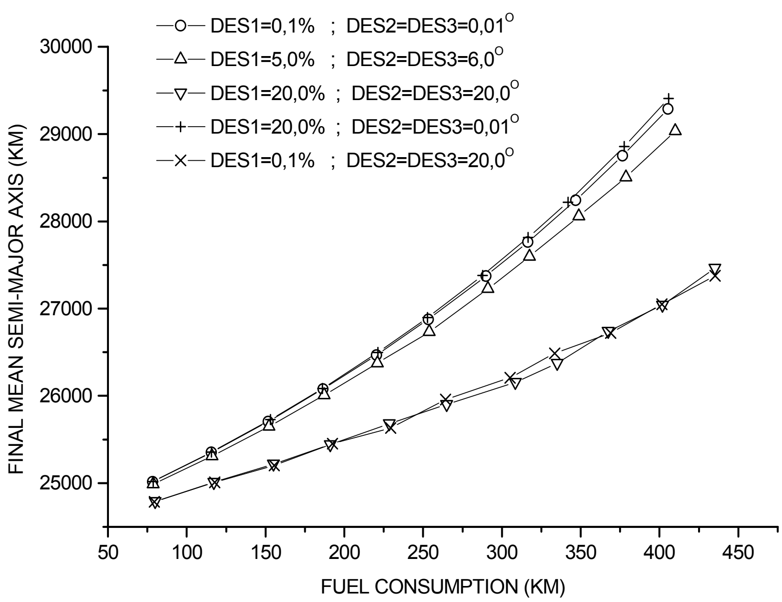

Figure 2 – Final Mean Semi-major axis vs. Fuel Consumption, POR

The Figure 2 confirms the results of the theoretical orbits obtained before. That is, only the superposed direction deviation causes loss of the mission fuel in the obtainment of the semi-major axis. These results do not depend of the kind of the orbits (T or P). These both transfers maneuvers were realized under constant thrust. The effect of the variable thrust we present in the Figures 3 and 4.

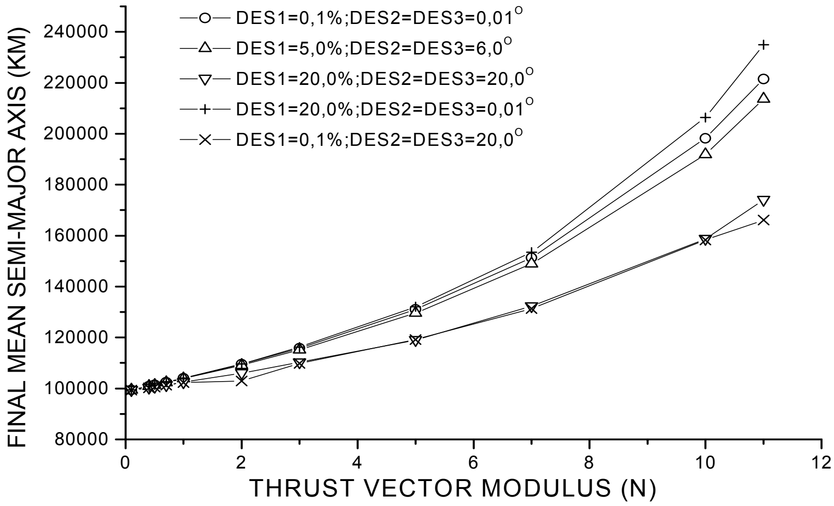

Figure 3 – Final Mean Semi-major axis vs. F, TOR

The behavior is similar to the fuel consumption case. This result was expected because there is one direct and simple relation between the fuel consumption and the thrust vector applied through the burns. But, is important observe that the strong direction deviations interferes in the final mean semi-major axis values.

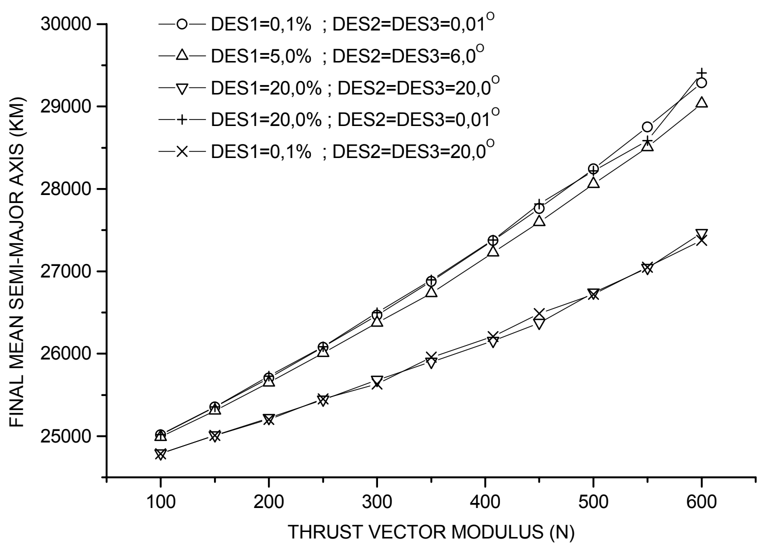

Figure 4 – Final Mean Semi-major axis vs. F, POR

We can observe in this figure that the qualitatively the results for the practical orbits are similar to that the theoretical orbits. Besides this, there is other important result, that is, a higher propulsion can inhibit the deviations effects, because we observed that strong deviations with thrust equal requires not much corrections maneuvers. In this way, we can use the non-ideal propulsion system to control the final mean semi-major axis, for example, if we have availability of the fuel on board. It is possible, because, when the superposed direction deviations are strong, the increasing of the motor power stabilizes their influence, minimizing their effects.

In the Figures 5 and 6, we present the eccentricity evolution as function of the systematic and operational superposed thrust deviations, respectively.

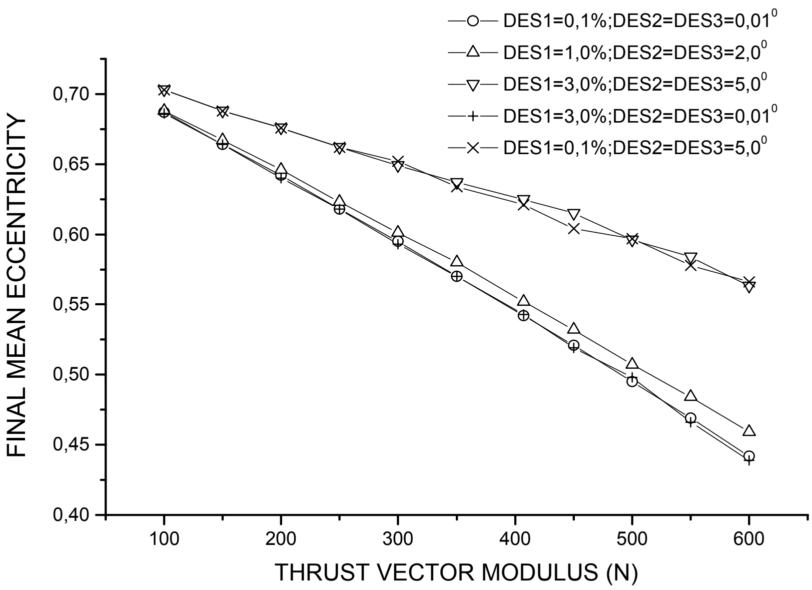

Figure 5 – Final mean eccentricity vs. F, POR

We observe in this figure the effect of the variation of the thrust applied in the final mean eccentricity values. The increasing of the thrust applied provides the decreasing of the eccentricity, in general. The strong superposed direction deviations effects are stabilized by the motor power through near linear relation between them. The final transfer ellipsis is deformed in any case, but it can be closed to the final nominal by application of the major thrusts. The operational superposed deviations effects were too analyzed inside the eccentricity values during the burns arcs. We observed that occurs behavior of the final mean eccentricity evolution w.r.t. the motor power similar to the systematic case for this dynamic under superposed operational deviations, during the thrust application. The decay is major for the systematic case. It do not occurs the stabilizing effect for the strong direction deviations observed in the systematic case. Therefore, the final transfer ellipsis is deformed and it can not be stabilized by the motor power. In the Figure 6 we show these numerical simulations for this case.

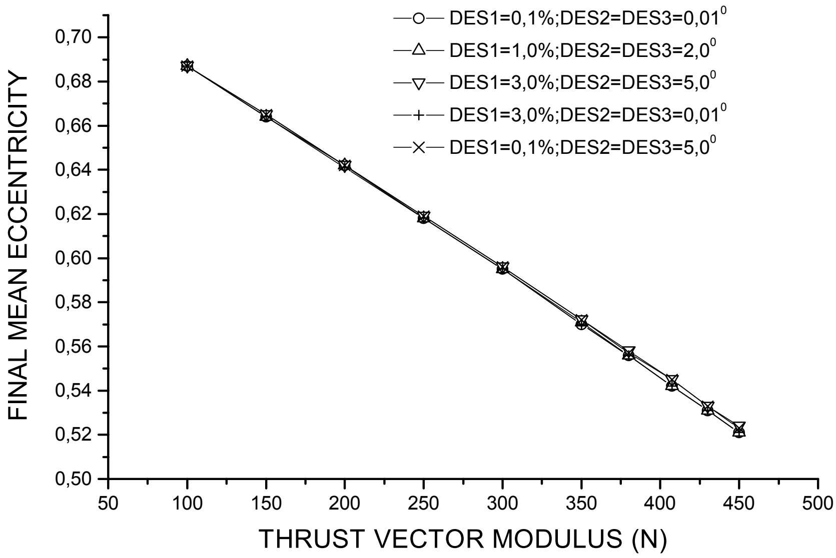

Figure 6 – Final mean eccentricity vs. F, POW

These results showed that only for the systematic direction deviation is possible the use of the motor power to stabilizing the eccentricity values and that the operational direction deviations effects are little than them.

The numerical analysis for the transfers orbits inclination is presented in the Figures 7 (systematic case) and 8 (operational case), in the following.

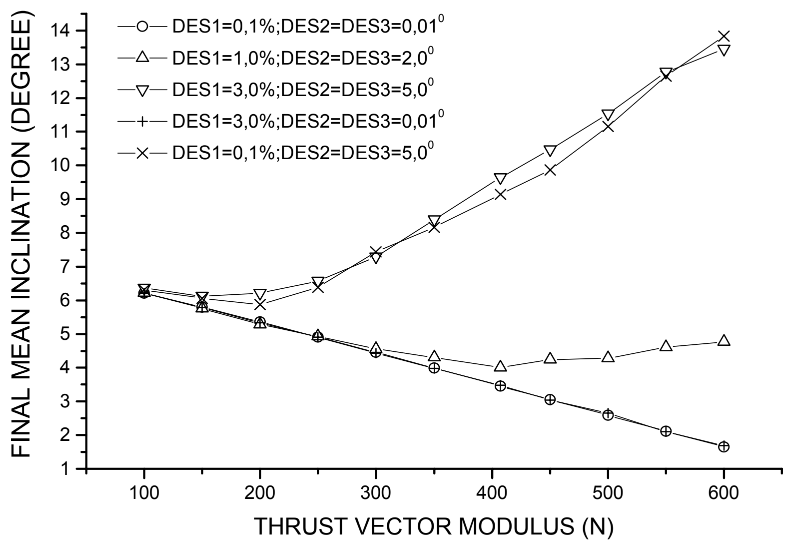

Figure 7 – Final mean inclination vs. F, POR

We can observe in this figure the increasing power motor amplifying the superposed direction deviations effects over the final mean inclination of the final transfers orbits. The general behavior of the inclination w.r.t. the increasing power motor is decreasing their values. But, when the direction strong deviations combination occurs, the inclination values are increased. It is shows that depending of the mission, the power motors can be used to stabilize the influence of their non-ideality w.r.t. the direction deviations. The small superposed direction deviations do not affected by power motors, but the strong superposed direction deviations are exaggerated. If the final nominal orbit demands inclination little than the initial orbit, then we can used the power motor as control to stabilize the final mean inclination values. The missions must incorporates variable and controllable thrusters systems to attain this purpose. The inclination behavior for the operational superposed direction deviations effects when the thrust applied is variable is showed in the Figure 8.

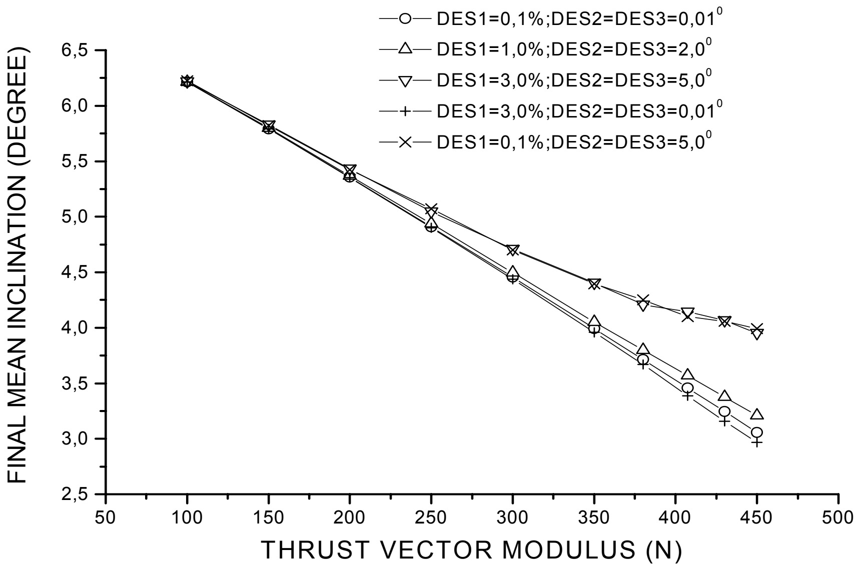

Figure 8 – Final mean inclination vs. F, POW

In the Figure 8 we observe that the effect of the operational superposed direction deviations over the final mean inclination values is not so strong w.r.t. the results of the systematic case. The effects strong direction deviations combinations do not stabilized by power motor efficiently as the before case. In other hand, we observe that the non-ideal thrusters systems provides inhibition of the direction deviations effects. So, the results are always different, depending of the kind of deviations (R,W). The values decay is similar to eccentricity, occurring stabilizing to more power motors under so strong operational case. This case is more close to the real thrusters burn case, because admits probabilistic deviations during each burn along the transfer arcs. Beside this results, it is important to observe these maneuvers are fuel consumption optimum, so, in these non-ideal maneuvers occurred safe of the fuel under superposed direction deviations systematic or operational. The modulus thrust deviation did not influence in this results.

CORRECTION MANEUVERS – NON SUPERPOSED THRUST DEVIATIONS

In this section we present the simulations results about the correction maneuvers only for the non superposed thrust deviations cases. We analyzed the number of correction maneuvers to vehicle attains its final nominal orbit, through the additional burns small arcs and, the extra fuel consumption and extra time needed to reach them. In this simulations we considered individual and systematic deviations only. There is not superposed thrust deviations. This results we present in the Table 3 in the following.

TABLE 3 – EXTRA FUEL CONSUMPTION TO CORRECTION MANEUVERS

DES1	**Extra fuel consumption**	**Correction maneuvers**	**Extra time burn**
0,5%	5,19%	1	4,70%
1,0%	5,84%	1	4,82%
2,0%	8,58%	2	6,47%
5,0%	16,09%	3	10,59%
10,0%	30,39%	4	18,53%
DES2	**Extra fuel consumption**	**Correction maneuvers**	**Extra time burn**
$1,0^0$	6,21%	3	6,29%
$2,0^0$	5,35%	2	5,41%
$5,0^0$	5,64%	2	5,65%
$10,0^0$	6,25%	2	6,18%
DES3	**Extra fuel consumption**	**Correction maneuvers**	**Extra time burn**
$0,5^0$	8,02%	4	19,97%
$1,0^0$	2,84%	3	-0,93%
$2,0^0$	15,00%	3	10,13%
$5,0^0$	2,28%	3	-2,56%
$10,0^0$	29,13%	5	23,73%

This table presents several important results. They were obtained to theoretical maneuvers (DES1 and DES2) and practical maneuvers (DES3). We observe that the effects of the modulus deviations are verified in the corrections arcs. The extra fuel consumption and extra time burn present near linear dependence relation with the modulus deviations (DES1), increasing their values when it is increased. The quantify of the correction maneuvers increasing too. These maneuvers do not depend of the direction thrust deviation, so, the "pitch" and "yaw" angles are constants in this transfer. They provide the nominal direction to thrust application in each burn. The results under DES2 only, but for the same maneuvers, show important information. The increasing of the "pitch" individual deviations requires little extra fuel consumption to realize the correction maneuvers than the modulus individual deviations case required. It shows the strong influence of the individual modulus thrust deviation through the correction maneuvers. In general, we observe too that the DES3 deviations provide more damages in the maneuvers than others deviations, because require more correction maneuvers. But, we can observe too that the extra fuel consumption do not presents linear dependence with the “yaw” individual deviations. It occurs because the problem analyzed requires constrains satisfaction during the thrusters burns. The final nominal transfers have constrains to 6 keplerian elements. To satisfy all six constrains the cost missions turn so strong. During the missions must one chose the more important keplerian elements to satisfy or decide what is possible to realize with available fuel. Therefore, the Table 3 shows the results of the systematic individual yaw deviations under satisfaction, mainly, semi-major axis and inclination, because this is the practical maneuver, that is out-plane maneuver, in that the yaw angle is very strong during the change of the planes.

In general we observe that when the thrust individual deviations increasing, more correction maneuvers are required, therefore, more extra fuel consumption and time burn are required. These extra fuel consumption in DES2 is relatively little for the DES1 case, in in-plane maneuvers. The out-plane maneuvers will require more extra fuel consumption with DES3 increasing and number of the correction maneuvers increasing with constrains satisfaction of the all the keplerian elements.

CONCLUSION

This paper has presented results about the feasibility of the orbital transfers w.r.t. power motors and fuel consumption. We studied two kind of transfers maneuvers, in-plane and out-plane maneuvers. We found the performance thrusters motors curve, so that, the more powering motors spends more fuel and can reach their aims rapidly. They show the space missions feasibility under superposed systematic or operational thrust deviations through the some keplerian elements (semi-major axis, inclination and eccentricity) and fuel consumption. We verified too that the variable thruster systems can be used as mission control element to stabilize the superposed direction deviations effects. In general, the systematic direction deviations effects are more strong w.r.t. the operational deviations in all the studied cases. Besides this, the correction maneuvers under individual thrust deviations are more required for the direction deviations. In the theoretical correction maneuvers (in-plane) the modulus thrust deviations affects more than the pitch deviations, therefore, spending more extra fuel, but inside interest practical deviation range they present similar results. The out-plane correction maneuvers are strongly affected by yaw deviations and turn not feasible to reach all the constrains in the keplerian elements of the final orbit. These results allow preliminary analysis of space missions through the power propulsion motors efficiency and the available fuel to realize correction maneuvers and/or constrains satisfaction.

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