THRUST / MASS ONLINE ESTIMATION OF A SATELLITE LAUNCHER

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Abstract. The guidance algorithm design of Brazilian Satellite Launcher, denoted by VLS, is done by using a mathematical model which takes into account the propulsion produced by the motor rocket and the mass behavior due to the propellant consumption. The thrust profile is given in the form of three curves called nominal, superior and inferior. The inferior and posterior curves are used as limiters between the real curve of thrust and propellant mass must remain. Then, a method to provide during the flight (online) a profile of the thrust and propellant mass using the two limiting curves, as close as possible to real thrust, is useful to increase the efficiency of the guidance algorithm and to reduce the orbital dispersion of the satellite.

The ideal flight occurs when the real profiles of mass and thrust are equal to nominal, but it is a difficult situation to happen. Therefore, a good estimation of the real curve is necessary such that the uncertainty can be reduced. This paper presents a methodology to perform an online estimation of the thrust/mass curves such that they are as similar as possible to the real. Thereby, the simulation will be more consistent with reality, as it is showed by the results.

1 Introduction

1.1 The VLS

The Brazilian Satellite Launcher - VLS is a vehicle with 4 stages using a solid propellant. It has an orbit insertion capability around 750 Km and can transport until 185 Kg of payload.

The method described in this work is sufficiently general to be applied in similar cases, where one want to obtain in real time the estimate of thrust and mass of a Satellite Launcher that uses solid propellant. However, this method was developed to be applied in the Brazilian Satellite Launcher (VLS).

1.2 The Guidance Algorithm – GUIA [1]

GUIA algorithm has as function the guidance of the VLS. Figure 1 shows a resume of the events which happen during the flight of the VLS, where it is possible to observe the guidance algorithm is executed during the third stage.

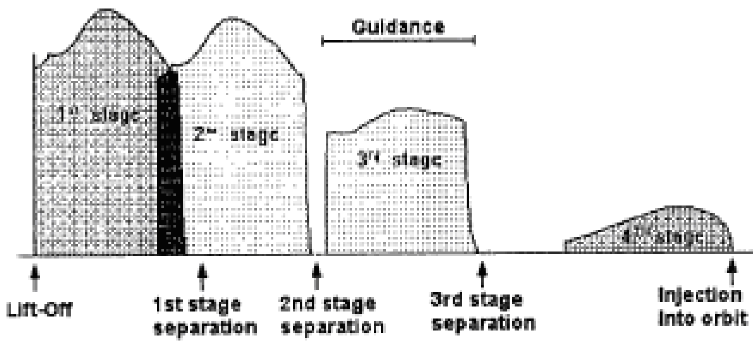

Figure 1. Resume of the events which happen during the flight of the VLS.

During the flight, mainly on the first and second stages, the vehicle suffers disturbances that move it away of the nominal conditions. To correct this problem the guidance command produces, based on the instantaneous conditions of flight (velocity and position), on the energy conditions of the vehicle (thrust and mass), and on the final orbit to be reached by the satellite, the reference to the attitude control system. Thus, GUIA produces a suborbital trajectory so that the vehicle reaches a transfer orbit with pre-specified parameters, which it is not possible to be done in the nominal case.

Due to necessity to have the information about the energy of the vehicle to execute the guidance algorithm, it is important to have a good approach for the thrust and mass profiles. Otherwise, the efficiency of the algorithm will be impaired. In spite of, the actual guidance algorithm uses a rude approach for the thrust and mass of the vehicle. This paper presents a methodology to resolve this problem.

Figures 2 and 3 show the thrust and mass used in the guidance algorithm, respectively. These approximations are used to become possible for writing the literal expressions to velocity and position of the vehicle.

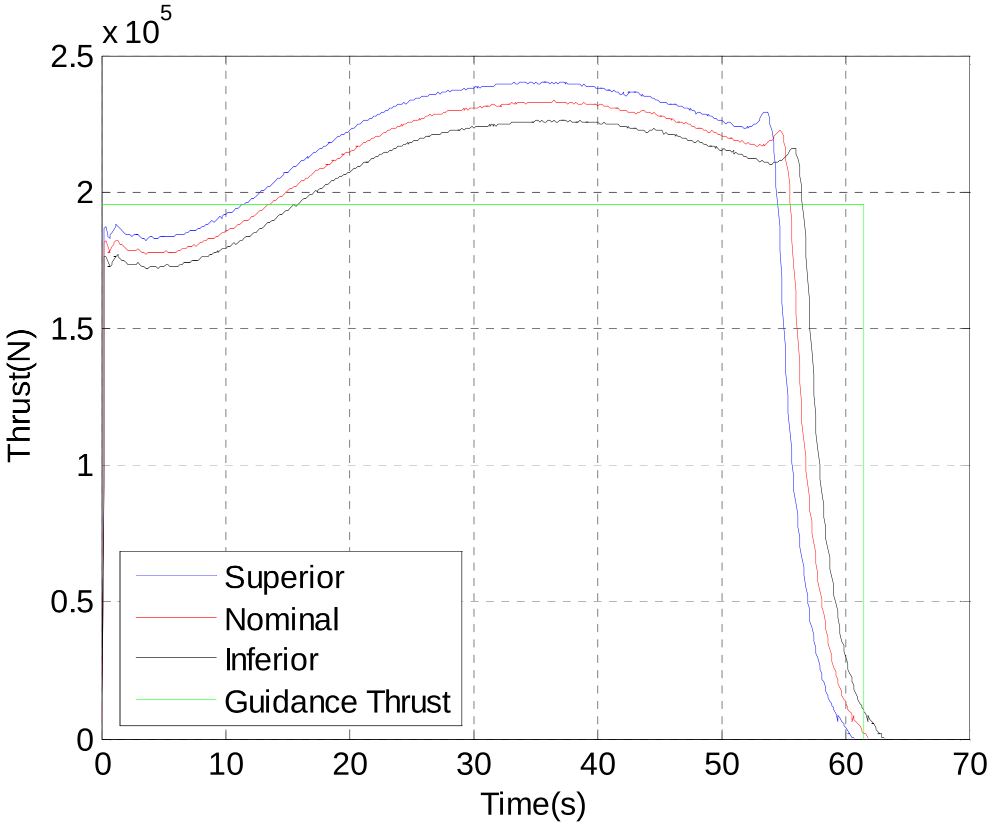

Figure 2. Thrust curves: Nominal, Superior, Inferior and Guidance Thrust.

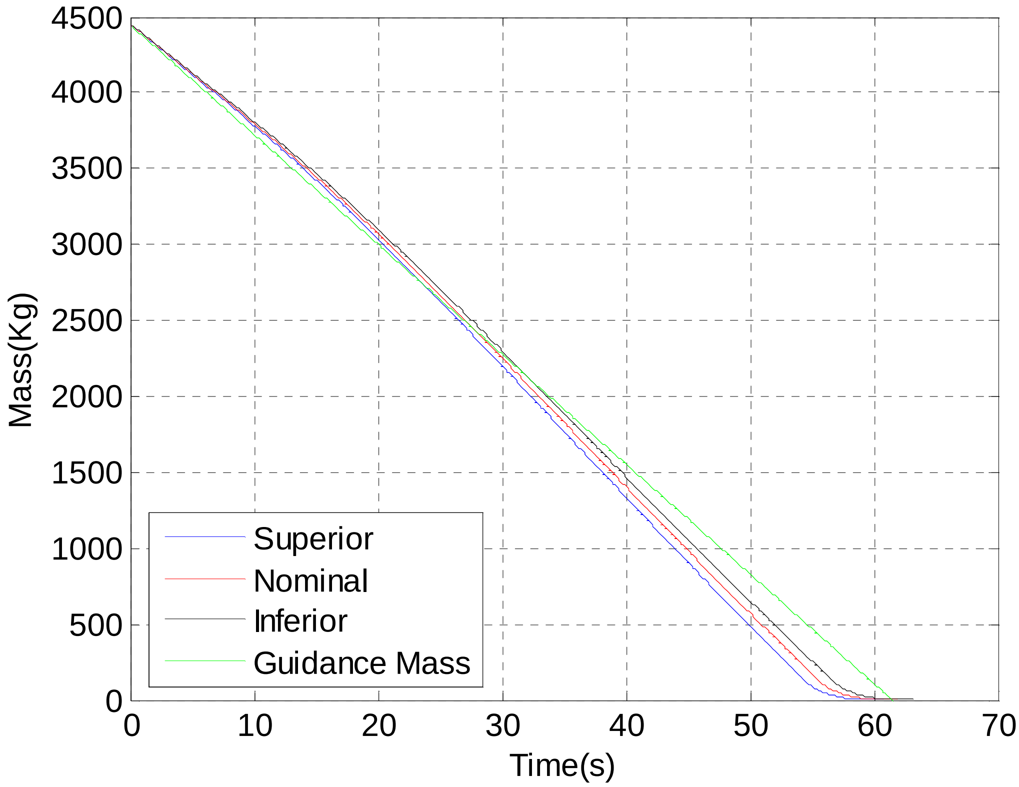

Figure 3. Propellant Mass curves: Nominal, Superior, Inferior and Guidance Mass.

1.3 Mean Quadratic Error – MQE

The criterion of the Mean Quadratic Error measures the mean deviation of the variations of the simulated values regarding the reference values. A smaller MQE results in a better adherence of the simulations to the reference.

The value of the Mean Quadratic Error is calculated as described in equation 1:

$$MQE = \frac{\sum_{i=1}^{N} (X_{\text{calc}} - X_{\text{real}})^2}{N} \tag{1}$$

Where:

- X_{calc} = calculated value of the variable;
- X_{real} = real value of the variable and;
- N = number of measurements.

1.4 Simulation Program – ADAGA [4]

The control systems complexity of a satellite launcher and the high cost of a simple test flight lead to the application of digital simulations during the control system project of the satellite launcher.

ADAGA is a useful tool to the VLS project. It allows accomplishing preliminary studies to the vehicle's flight from lift-off up to orbit insertion.

Using this software, it is possible to evaluate the performance of the system, and a sensitivity analysis of the model parameters. Due to the fact that, a priori, the analytic statistical analysis methods are inadequate to the problem in question, the software uses Monte Carlo technique where artificial samples or data are generated by using random number generator and random statistics with regard to the factor of interest, with the objective for reproducing as close as possible the real disturbances and simulate the dispersions of the vehicle that can occur during the flight.

2 Thrust/Mass Profile

The thrust force produced by the rocket motor and the consumption of propellant mass of the third stage of VLS are given in form of three curves, describing the nominal, superior and inferior. Figures 2 and 3 show the thrust and propellant mass profiles, respectively.

3 The Online Estimation

This work presents a methodology to estimate online the values of the thrust and mass as close as possible of the real values. It is achieved by writing the thrust and mass curves as functions of a single random parameter defined as alpha (α), where -1 $\leq \alpha \leq$ 1, and of constants defined as *aes*, *aei*, *ams*, *ami*, *ats* and *ati*, whose values must have been previously determined ([2],[3]). For this case, the values of the predetermined parameters are showed on Table 1, where:

- *aes* is a constant for the superior thrust force;
- *aei* is a constant for the inferior thrust force;
- *ams* is a constant for the superior propellant mass;
- *ami* is a constant for the inferior propellant mass;
- *ats* is a constant for the superior burning time and;
- *ati* is a constant for the inferior burning time.

Parameter	Values
aes	1,0306
aei	0,9705
ams	1,0000
ami	1,0000
ats	0,9800
ati	1,0200

Table 1. Vaues to the constants.

This procedure will generate curves of thrust and mass with dispersions inside the limits defined by the curves superior and inferior. For α equal to -1, 0 and 1, the estimated curve must be equal to the inferior curve, nominal and superior, respectively. Thus, for any value of α, the curve will be inside the specified limits.

The expression of the acceleration produced by the simulation program ADAGA [4], caused by the thrust of the rocket motor, can be expressed by the equation 2:

$$a_c(t) = \frac{F(t)}{M_0 - (M(1) - M(t))} \tag{2}$$

Where the thrust and mass of the Satellite Launcher can be obtained as following:

$$F(t) = \begin{cases} (1+(aes-1)*\alpha(t))*F_N(t), & \text{if } \alpha \geq 0 \\ (1+(1-aei)*\alpha(t))*F_N(t), & \text{if } \alpha < 0 \end{cases} \tag{3}$$

$$M(t)=\begin{cases}(1+(ams-1)*\alpha(t))*M_N(t), & \text{if } \alpha\geq 0\\ (1+(1-ami)*\alpha(t))*M_N(t), & \text{if } \alpha<0\end{cases} \tag{4}$$

$$t=\begin{cases}(1+(ats-1)*\alpha(t))*t, & \text{if } \alpha\geq 0\\ (1+(1-ati)*\alpha(t))*t, & \text{if } \alpha<0\end{cases} \tag{5}$$

Where:

- a_C is the acceleration of the launcher;
- F is the thrust force of the launcher;
- M_0 is the total mass of the launcher on the ignition time of the rocket motor;
- M is the propellant mass of the rocket motor;
- F_N is the nominal thrust force of the rocket motor;
- M_N is the nominal propellant mass of the rocket motor and;
- t is the burning time of the propellant.

Applying (3) and (4) in (2), one has:

$$a_C(t)=\begin{cases}\dfrac{((1+(aes-1)*\alpha(t))*F_N(t))}{M_0-((1+(ams-1)*\alpha(t))*M_N(1)-(1+(ams-1)*\alpha(t))*M_N(t))}, & \text{if } \alpha\geq 0\\[2ex] \dfrac{((1+(1-aei)*\alpha(t))*F_N(t))}{M_0-((1+(1-ami)*\alpha(t))*M_N(1)-(1+(1-ami)*\alpha(t))*M_N(t))}, & \text{if } \alpha<0\end{cases} \tag{6}$$

Where the real value to $a_C(t)$ is available during all the flight.

Solving the equation (6) as function of α, one has:

$$\alpha(t)=\frac{-F_N(t)+a_C(t)*M_0+a_C(t)*M_N(t)-a_C(t)*M_N(1)}{-F_N(t)+aes*F_N(t)+a_C(t)*M_N(t)-a_C(t)*ams*M_N(t)-a_C(t)*M_N(1)+a_C(t)*ams*M_N(1)},$$

$$\text{if } \alpha\geq 0 \tag{7}$$

and

$$\alpha(t)=\frac{F_N(t)-a_C(t)*M_0-a_C(t)*M_N(t)+a_C(t)*M_N(1)}{-F_N(t)+aei*F_N(t)+a_C(t)*M_N(t)-a_C(t)*ami*M_N(t)-a_C(t)*M_N(1)+a_C(t)*ami*M_N(1)},$$

$$\text{if } \alpha<0 \tag{8}$$

Using the real value of $a_C(t)$ in the equation 7 and equation 8, one obtains two values of α. A small adjustment in the algorithm is used to evaluate which one will be used. Using the value of α in the equations 3-5, one obtains the new profile of the thrust and mass.

As a discrete-time system, a new value of α is calculated at certain instants of time, equally spaced by an amount of T, called sampling period. For each sampling period, a new α is calculated instantly and it is used until the next α be calculated. The curve of α is shown in Figure 4. After obtaining in real time the value of α, a new thrust and mass curves are generated for the guidance algorithm. Such curves are used to estimate the remaining energy of the Satellite Launcher, which is essential information for the guidance algorithm. The more precise, will be greater the possibility of executing the mission of the Satellite Launcher with success, that is the insertion of a satellite in a specific orbit.

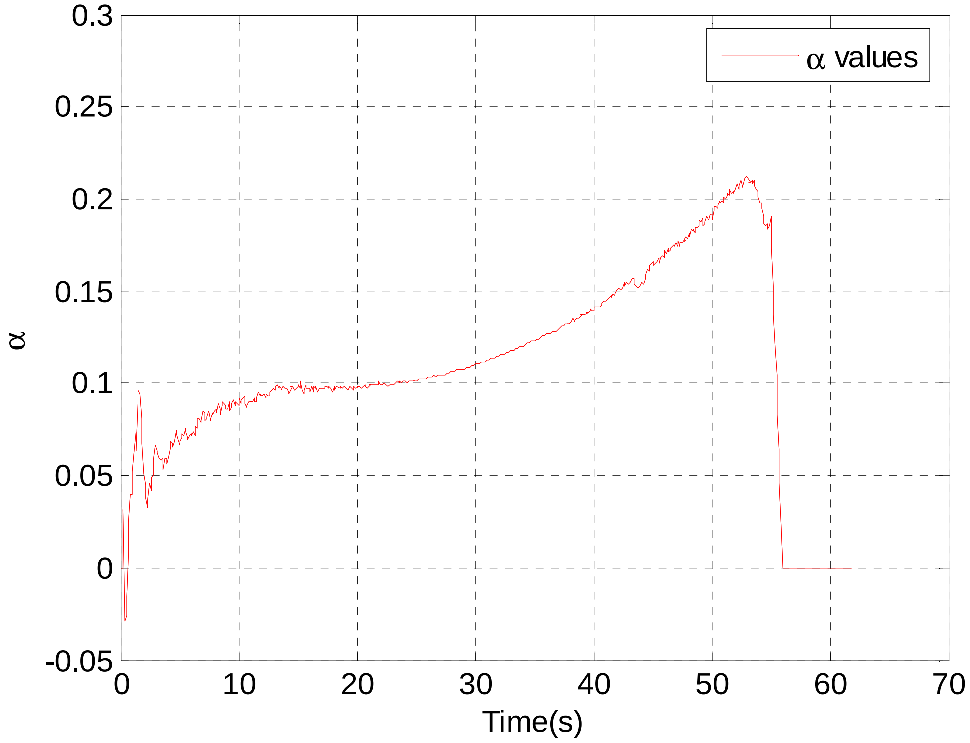

Figure 4. α x Time.

4 Results

The curves of the thrust can be viewed in Figure 5 and 6, where it is possible verify that the guidance curve is totally different of the real curve (ADAGA). On the other hand, the online curve is very similar to real curve. The same results to the mass can be viewed in Figure 7 and 8.

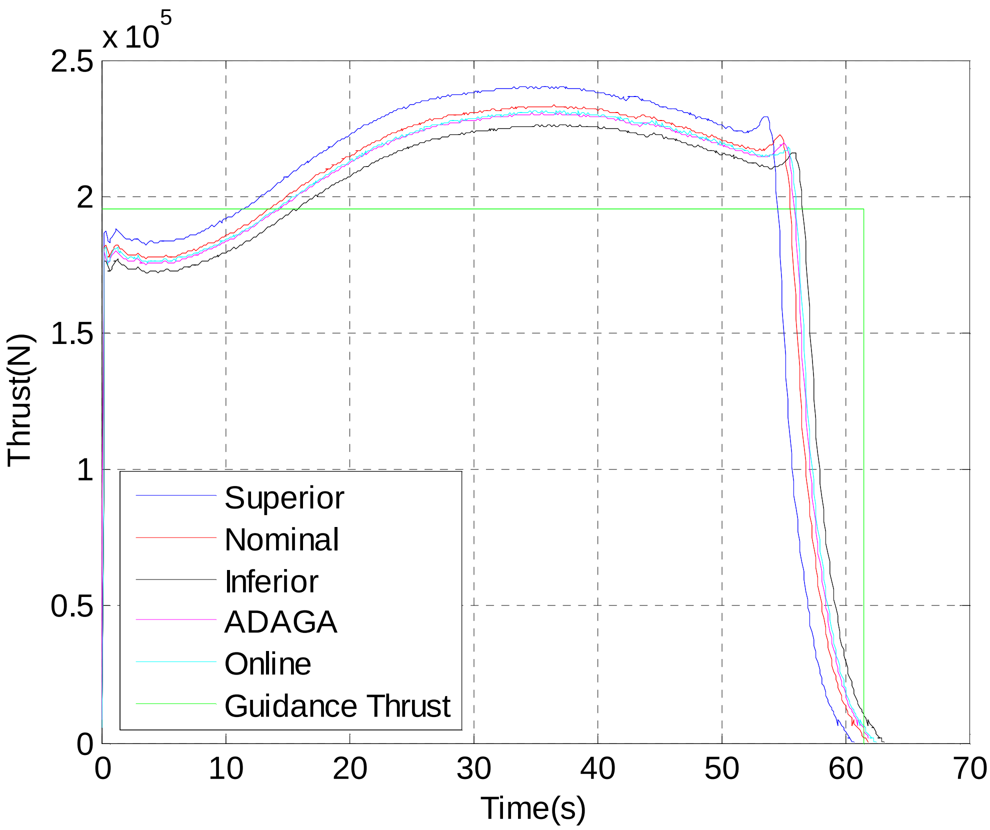

Figure 5. Thrust curves: Nominal, Superior, Inferior, ADAGA, Guidance Thrust and Online.

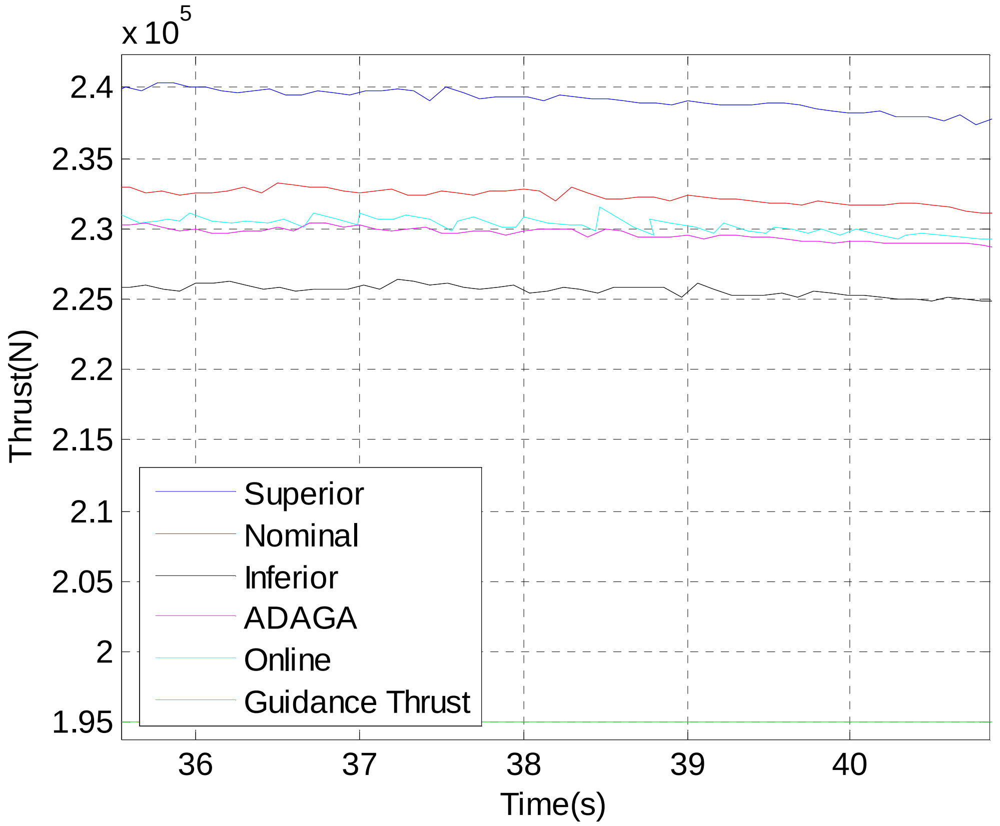

Figure 6. Thrust curves with Zoom: Nominal, Superior, Inferior, ADAGA, Guidance Thrust and Online.

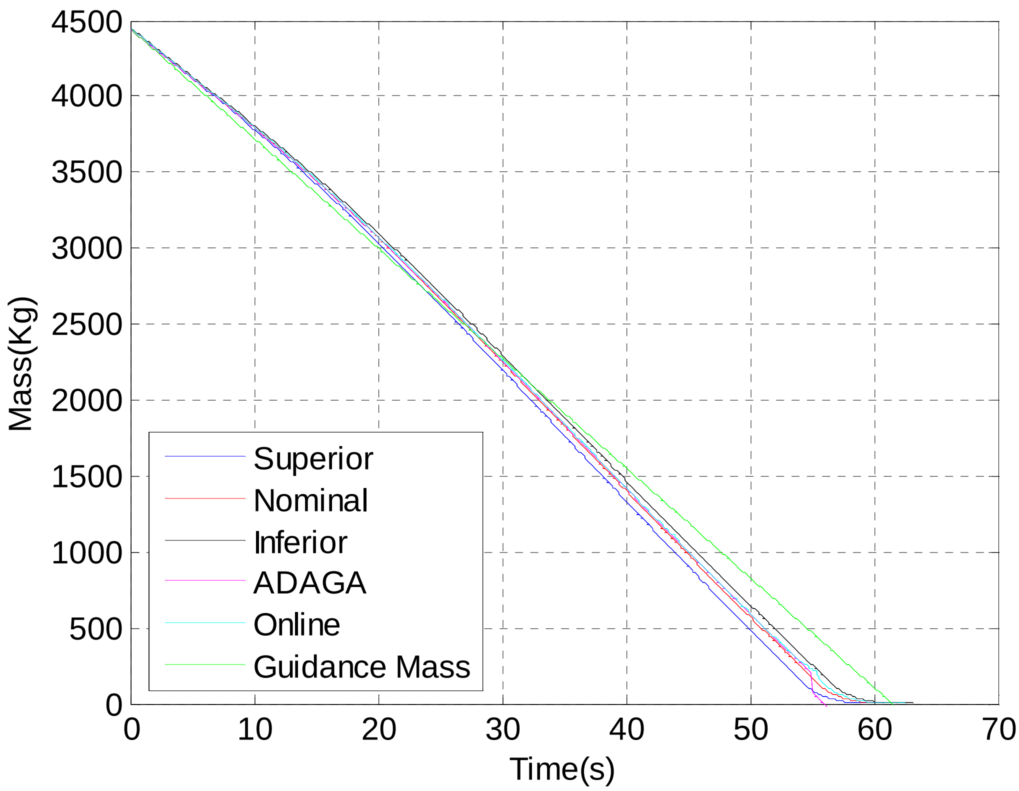

Figure 7. Mass consumption curves: Nominal, Superior, Inferior, ADAGA, Guidance Mass and Online.

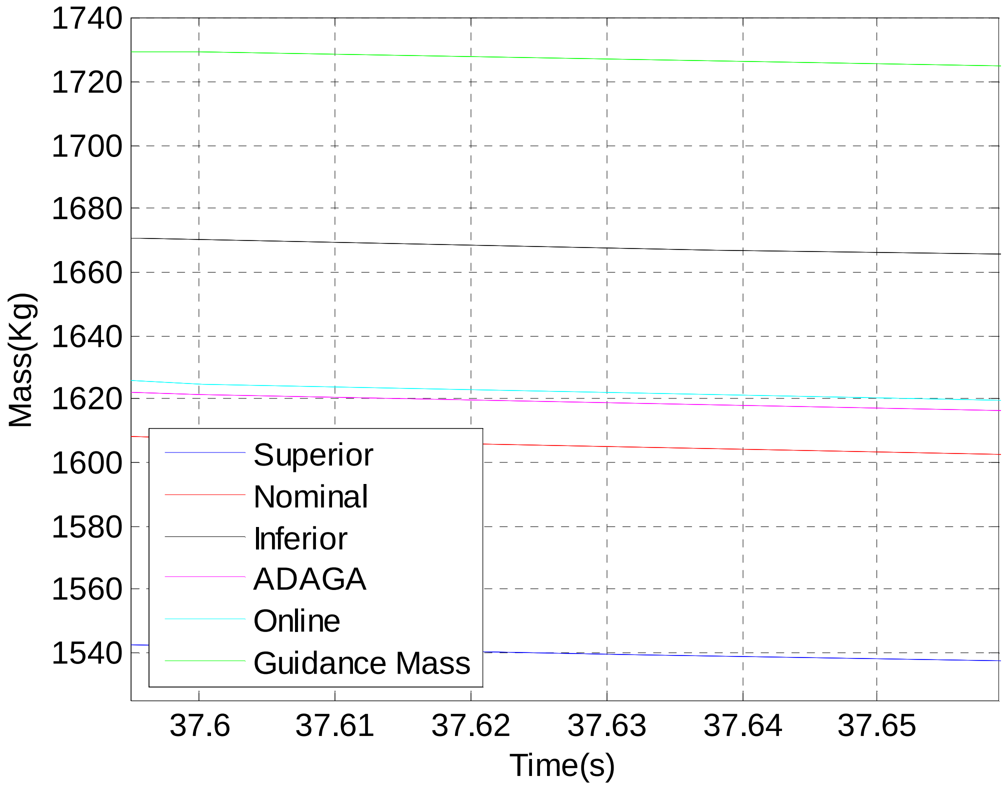

Figure 8. Mass consumption curves with Zoom: Nominal, Superior, Inferior, ADAGA, Guidance Mass and Online.

To evaluate the efficiency of this methodology, were done 600 simulations using Monte Carlo's method to generate random profiles of the thrust and mass during the execution of simulations. Mean Quadratic Error was the criterion used to do this analysis. Applying the equation 1, the results are shown in figure 9, where it is possible to verify it was obtained a smaller MQE to the Online method in 100% of the cases studied, to both thrust and mass profiles.

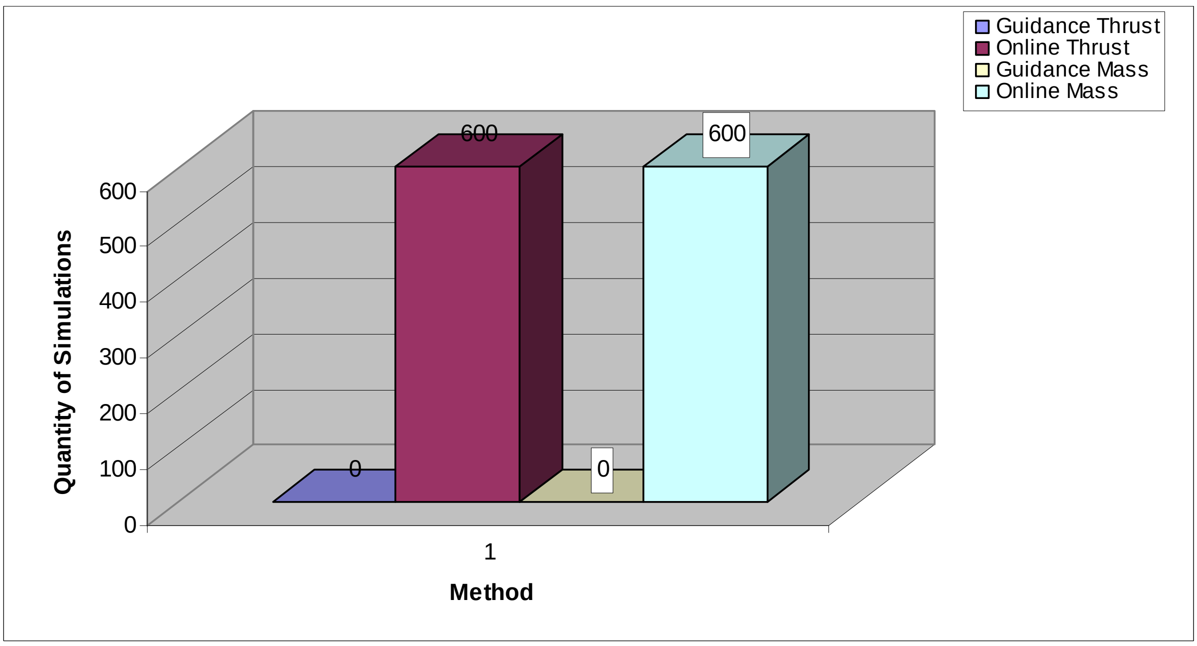

Figure 9. Quantity of simulations that each method presented a better result.

5 Conclusion

This paper presents a methodology to estimate online the thrust and mass profiles as similar as possible to the real profile. In agreement with the criterion of Mean Quadratic Error (MQE), the Online method presented in 100% of the cases a better result than using the Guidance Algorithm. Moreover, the online curves are very similar to real curves. Consequently, the methodology here proposal is sufficiently capable of being used to get a better estimate of the remaining energy of the Satellite Launcher, improving the guidance algorithm. As a result, one provides a successful mission which means the insertion of a satellite in a predetermined orbit.

This methodology was developed to be applied in the Brazilian Satellite Launcher (VLS). However, it is sufficiently general to treat similar cases, where one wants to obtain in real time a good estimative of thrust and mass of a rocket motor using solid propellant.

6 References

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