A Guidance Algorithm for a Satellite Launch Vehicle with Controlled Last Stage

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Abstract

During the flight, a satellite launch vehicle is subjected to disturbances. If the vehicle continues to suffer these disturbances and no compensation is applied, the mission of the vehicle can be jeopardized. This article presents a closed loop guidance algorithm for the last stage of a satellite launch vehicle intended to minimize the effects of these disturbances on the overall launcher´s mission. This strategy calculates onboard the pitch angle profile to the attitude control system. In order to evaluate the performance of this guidance strategy, the Monte Carlo simulation was performed. The results obtained showed the efficiency of this algorithm.

1. Introduction

Due to the dispersions and disturbances that occur during the flight of a satellite launch vehicle, the nominal trajectory can not be fulfilled, as well as the vehicle mission. For this reason, it is not recommended to use the nominal trajectory data (attitude profile to the whole flight, as well as the ignition and separation time for each engine) to conduct the payload to the desired orbit, mainly for the upper stages. Thus, it is necessary a guidance algorithm to recalculate some data onboard, in order to reduce the effects of the disturbances on the vehicle flight and, consequently, to reduce the dispersion on the final orbit parameters.

In [1] it is presented a guidance algorithm for the uncontrolled last stage of a satellite launch vehicle that uses solid propellant. It calculates a proper ignition time to the last stage and the proper attitude in this time. These calculations are based on real navigation data, desired orbital parameters, the velocity and position impulsive increment given by the engine of the last stage, and its burning time. This guidance algorithm is performed only once just after the separation of penultimate stage. After the execution of this algorithm, the vehicle will fly in coasting phase until the ignition of last stage. During this time, the last-stage/satellite assembly is orientated. After the ignition of the last engine, the attitude of this stage remains the same until its burnout.

However, in [2] results were presented which showed that the methodology proposed in [1] is able to reduce the dispersion around the nominal orbit when the disturbances occur during the last stage flight, but not satisfactorily. Obviously, it happens because these disturbances occur after its execution.

In order to obtain a solution for this problem, as proposed in [3], in addition to the calculations done by the algorithm presented in [1], this article presents a guidance algorithm that calculates periodically onboard, during the burning of the controlled last stage, a new pitch angle as reference for the control system.

The obtained results using Monte Carlo simulation showed that this new guidance algorithm is better than the algorithm proposed in [1], by reducing the impact of the dispersions on the overall mission performance of a satellite launch vehicle. For this particular case, the vehicle used to verify the performance of this algorithm was the Brazilian Satellite Launch Vehicle (VLS, acronym in Portuguese) (see [4] for more details about VLS).

The article is organized as follows: the section 2 is devoted to the guidance algorithm for the last stage of a satellite launch vehicle; in section 3 the results are presented; and conclusions are found in section 4.

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2. Guidance Algorithm - GA

2.1 Guidance Algorithm Presented in [1] - GA1

The nominal trajectory pre-specified of the VLS contains the attitude profile to the whole flight, as well as the ignition and separation time to the VLS´s engines. However, due to the dispersions and disturbances that occur during the flight, the nominal trajectory is not fulfilled. Thus, since the last stage of VLS does not have velocity and attitude control, but it has only the spin stabilization, it is not appropriated to use the nominal value of ignition instant of the upper stage and its attitude in this time to conduct the satellite to the desired orbit.

So, VLS uses an algorithm called pointing algorithm that calculates the proper ignition time (t_{ig}) and the proper attitude ($\theta_{r_{4st}}$ and $\psi_{r_{4st}}$) in this time for the last stage. These calculations are based on real navigation data, on desired orbital parameters, and on the velocity and position impulsive increment given by the engine of the last stage and its burning time. This algorithm plays a role of guidance loop (see [1]) in order to obtain a proper transfer from actual Keplerian orbit to a final circular orbit. By assuming that no disturbance occurs during the coast phase (phase between the 3rd-stage burnout and the ignition of 4th-stage) to change the present Keplerian orbit, this algorithm is performed once just after third stage separation.

The strategy proposed is based on the impulsive orbit transfer. It is considered that all the 4th-stage energy is applied as an impulse. To compensate the impulsive supposition, a correction factor is obtained for impulsive ignition time, which results in the right ignition time t_{ig}, whose corresponding radius in the ascending phase of the Keplerian orbit is R_{ig}.

The **GA1** foresees safe modes. The alternatives are the last stage ignition in the apogee of the Keplerian orbit, or in the radius R_{ig} during the descending phase of the path. In both cases a minimum of eccentricity is looked for.

This algorithm is very simple, making its real time implementation possible in the onboard computer. After its execution, the pitch-over movement is executed using cold gas thrusters to point the last-stage/satellite assembly towards to attitude obtained by the **GA1**.

2.2 Guidance Algorithm Presented in this Article - GA2

As proposed in [3], in addition to the calculations done by the algorithm **GA1**, this guidance algorithm **GA2** calculates periodically onboard, during the burning of a controlled last stage, a new pitch angle as reference for the control system.

At the time of last stage ignition, its attitude $\theta_{r_{4st}}$ and $\psi_{r_{4st}}$ previously calculated by the **GA1** algorithm remain constant during δt seconds. After δt seconds, a new pitch angle is calculated online by the **GA2** algorithm, differently of $\psi_{r_{4st}}$ that remains the same until the burnout of the last stage. To have a closed-loop solution, $\theta_{r_{4st}}$ is recalculated periodically every δt seconds during the upper stage flight.

The new pitch angle is computed as follows:

- Calculate the profile of the specific force for the last stage:

$$a(t) = \frac{E(t)}{M(t)}, \tag{1}$$

  where $E(t)$ and $M(t)$ correspond to the total thrust and total mass of the last-stage/satellite assembly.

- Disregarding the gravitational acceleration, one has that the equations of the motion of the vehicle during the last stage flight on the particular inertial navigation frame are, according to Fig. 1, for $t_a \leq t \leq t_{bo}$:

$$a_{X_I}(t) = a(t).\cos(\theta_r).\cos(\psi_{r_{4st}}); \tag{2}$$
$$a_{Y_I}(t) = a(t).\sin(\theta_r); \tag{3}$$
$$a_{Z_I}(t) = -a(t).\sin(\theta_r).\cos(\psi_{r_{4st}}); \tag{4}$$

  where t_a is the actual time instant and t_{bo} is the last stage burnout.

- By using the information obtained by (2), (3) and (4), one simulates the flight from actual time t_a until t_{bo}, since we have the actual information of position and velocity provided by the navigation systems. Thus, the estimated position of the vehicle at the end of last stage flight ($H_{t_{bo}}$) is obtained, as well as the altitude related to the apogee and perigee at t_{bo} (H_{Apogee} and $H_{Perigee}$, respectively).

- To solve the guidance problem, it is necessary to find the value of θ_r that minimizes the following cost function:

$$J = C_{11} * \left|H_{t_{bo}} - H_{des}\right| + C_{22} * \left(H_{Apogee} - H_{Perigee}\right), \tag{5}$$

where H_{des} is the desired altitude to the final orbit. The values for C_{11} and C_{22} are constant chosen by the designer.

- The angle θ_r that produces the minimum value to the cost function J will be the new pitch angle $\theta_{r_{4st}}$ to be used as reference to the control system of the last stage. It will remain the same until the next value is calculated after δt seconds.

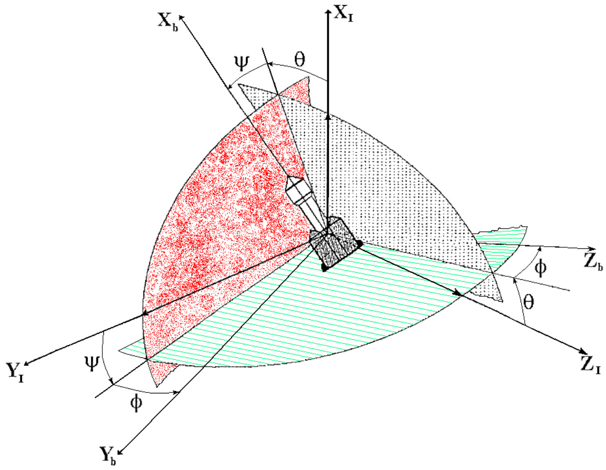

Figure 1: Inertial frame $[X_I\ Y_I\ Z_I]$ and Body frame $[X_b\ Y_b\ Z_b]$ used by VLS.

3. Results

To assess the performance of both algorithms **GA1** and **GA2**, digital simulations were done by using *MATLAB*. A Monte Carlo simulation was performed. The vehicle used to perform these simulations was the Brazilian Satellite Launch Vehicle. However, the **GA2** strategy can be used in other satellite launch vehicles whose last stage is controlled.

The simulations considered random profiles on the thrust and propellant mass of the first, second, third and fourth stages, as described in [5], considered dispersions on the structural mass of the vehicle, aerodynamic drag, ignition time and attitude misalignment of the last stage (to orbit injection).

Table 1 shows the cases that were simulated.

Table 1: Cases to be simulated using Monte Carlo simulations.

Sort of Disturbance	*CASE*			
	1	*2*	*3*	*4*
1st Stage Engine	X	X	X	X
2nd Stage Engine		X	X	X
3rd Stage Engine			X	X
4th Stage Engine				X
1st Stage Structural Mass	X	X	X	X
2nd Stage Structural Mass		X	X	X
3rd Stage Structural Mass			X	X
4th Stage Structural Mass				X
Aerodynamic Drag	X	X	X	X
Ignition Time of the Last Stage (t_{ig})				X
Pitch Angle of the Last Stage ($\theta_{r_{4st}}$)				X
Yaw Angle of the Last Stage ($\psi_{r_{4st}}$)				X

The obtained results of Monte Carlo simulation for the cases 1, 2, 3 and 4 are depicted in figures 2, 3,4 and 5, respectively. The number of simulation runs was 500 for each Monte Carlo simulation.

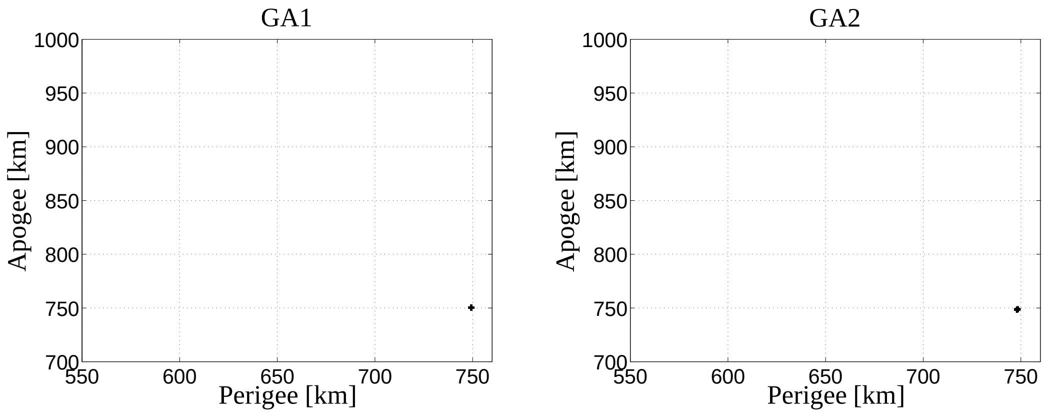

Figure 2: Results obtained by the algorithms GA1 and GA2 for the CASE 1 (random disturbances on the first stage of VLS).

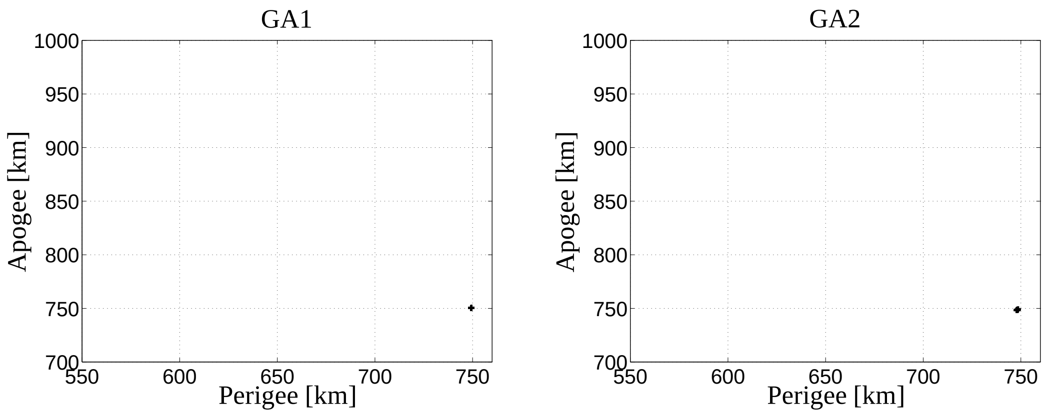

Figure 3: Results obtained by the algorithms GA1 and GA2 for the CASE 2 (random disturbances on the first and second stages of VLS).

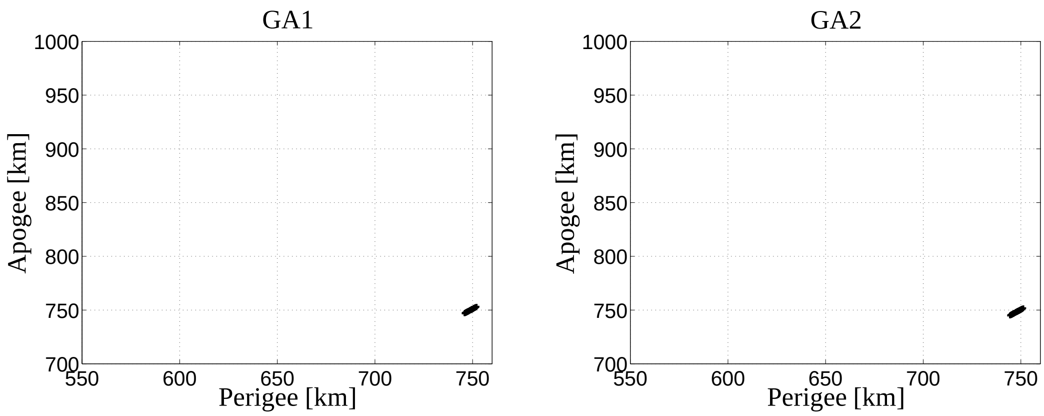

Figure 4: Results obtained by the algorithms GA1 and GA2 for the CASE 3 (random disturbances on the first, second and third stages of VLS).

4. Conclusions

A guidance algorithm was developed to reduce the effects of the disturbances that happen on the vehicle during the flight, thus reducing the dispersion around the final orbit parameters. This article presents two algorithm denoted by GA1 and GA2. The obtained results using Monte Carlo simulation showed that both GA1 and GA2 guidance algorithm worked properly when the the dispersions occur during the flight of first, during the flight of first and second,

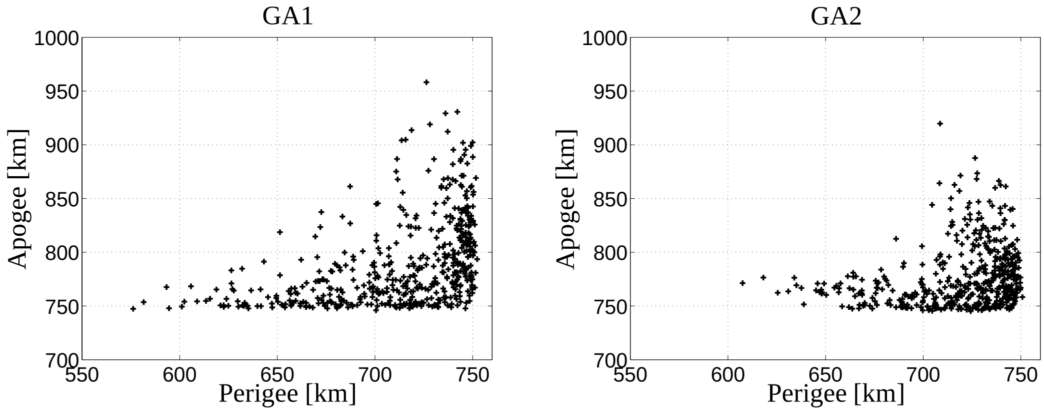

Figure 5: Results obtained by the algorithms GA1 and GA2 for the CASE 4 (random disturbances on the whole flight of VLS).

and during the flight of first, second and third stages (CASES 1, 2 and 3). Such results are depicted in figures 2, 3 and 4, respectively.

For the CASE 4, when the disturbances occur on the whole flight of VLS, the results showed that the performance of the new guidance algorithm proposed in this article (GA2) is better than the performance of the algorithm proposed in [1] (GA1), since that the new algorithm was able to reduce more effectively the impact of the dispersions on the overall mission performance of a satellite launch vehicle (see figure 5).

The vehicle used to verify the performance of this algorithm was the VLS, but such guidance strategy can be used by every satellite launch vehicle that uses liquid or solid controlled last stage.

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