Control System of Brazilian Launcher

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ABSTRACT

This work describes the whole functional structure of the control systems used in the Brazilian Satellite Launcher VLS. . It is focused the computational aspects and the implementation of the algorithms of the several loops that compose the control complex.

To accomplish its mission, the control complex must have suitable algorithms[1] and control loops, that should act during the powered and ballistics phases. This conception is related with the physical accomplishment of the vehicle that defines the actuators and the convenient sequence which they ones are used. The loops and algorithms have for objective to force the vehicle, at least, to come close to the reference path (or nominal), minimizing disturbances effects.

The navigation, guidance-loop compensation and control systems of VLS are reviewed with the respect to the system engineering. Operational requirements and design aspects determine the synthesis and the implementation of the system.

1. INTRODUCTION

The fundamental aim of the control complex is to guarantee that the vehicle accomplishes its mission. Due to the conception of the vehicle, the flight of VLS obeys a sequence of events that characterizes the several phases for which the vehicle must pass for the execution of its mission. Figure 1 illustrates this sequence.

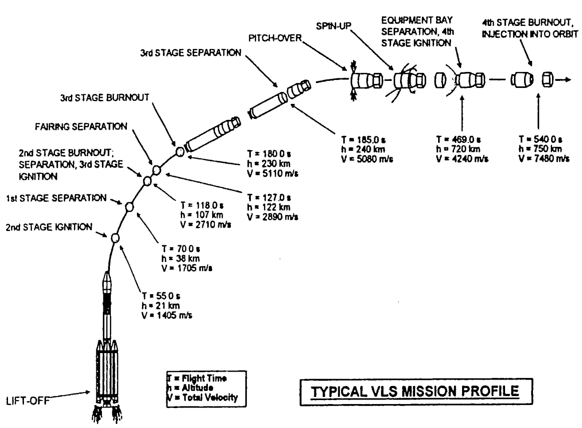

Fig.1 – VLS Sequence of Events

The VLS is a solid propellant vehicle with four stages and only the first three stages have active control. There is no control of thrust level of VLS. The last stage is spin stabilized[2] and the last action of the control system is to point the fourth stage - satellite to a certain inertial direction and fire the fourth stage. Then, the control complex includes: three attitude control loops, two guidance algorithms and a navigation algorithm. Three different types of actuators are used for the attitude control (one for thrust vector control). A digital computer fulfills all the calculation necessary to perform the control commands.

It is understood for algorithm a sequence of calculations that it will be executed by an on-board computer, based on real time measures, to obtain a control variable. It is understood for loop a feedback subsystem in which physical variables are controlled, throughout a period of time, through entities that excite or change the phenomenon - so called control variables.

The launch vehicle dynamics for attitude control refers to the rigid body behavior and the body bending characteristics, from which the vehicle control functions are derived. Flow diagrams, computational arrangements and specific components such as the inertial measurement unit show the implementation of the navigation, guidance and control systems. The off-nominal performance was considered through safe modes which permit that the different missions can be decided in-flight if the energy available is not enough to complete the nominal one.

2. SYSTEM FUNCTIONAL DESCRIPTION

Being the VLS a solid propellant vehicle, there is no control of the thrust level. Therefore, the control of the speed vector and, consequently, of its path is done in an indirect way through the control of its attitude - set of angles in relation to an inertial reference that defines a direction. Herewith, the propulsive and aerodynamic drag dispersion, besides the wind disturbances, cause changes in the path, even if the pre-established attitude profile is being performed precisely. Then, it is necessary to evaluate the real path and to correct the attitude profile commanded in order to minimize the difference between real path and the desired one. The loop that controls the changes in the path of the vehicle (displacement of the mass center) is called guidance loop.

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All the measured variables are referred to systems of coordinates or frames. They are: the body frame where the angular speeds are measured around its axes and where are affixed the actuators, and the navigation frame, this is inertial and geocentric, where the linear position vector and velocity vector are measured. In order to describe the relation between the frames, are measured the Euler angles, that define the attitude of the vehicle. A navigation algorithm is used to compute all those variables.

The attitude control, in the first three stages, uses movable nozzle as actuators. As the thrust vector of only one motor doesn't allow the torque generation in the three axes, it is necessary an auxiliary system – an on-off liquid thruster - for the roll control of the second and third stages. To compensate the deviations of the nominal path happened during the first and second stages burning, a guidance loop is used during the powered phase of the third stage. After the burning of the third stage, the direction to point the fourth stage and its ignition time are evaluated. To fulfill the pointing maneuver it is used another auxiliary actuator system (cold gas type).

Thus, only the first three stages have thrust vector control (TVC). The last stage is orientated before its ignition (during its ballistic phase) and spin stabilized[2]. Hence, the control complex has three attitude control loops - one for each actuator type (movable nozzle, liquid and cold gas thruster), two guidance loops and a navigation algorithm.

The VLS control system can be expressed according to the block diagram[1] shown in figure 2. It can be noticed two loops: an inner (attitude control) and an outer (guidance). The attitude control loops are working during the three first stages and are designed independently for each maneuver plane (pitch yaw and roll). The guidance loop only operates during the third stage burning to avoid the aerodynamic loads. Such algorithm generates the attitude reference for that flight phase. The attitude reference for the flight during the burning of the first two stages is pre-calculated and stored in the on-board computer. During the passive (ballistic) flight between the third and fourth stages it is necessary to pitch-over the vehicle. The attitude control loop to do this is called *basculamento*. In this phase, a called pointing algorithm play a role of guidance loop, calculating the attitude in that the last stage must be oriented and the instant of ignition of the fourth stage, for the satellite placement into the orbit.

The pitch-over loop *(basculamento)* works after the separation of the third stage, fulfilling the pitch over maneuver and keeping the final orientation up to the instant of command of spinning-up of the fourth stage. Then, the action of the control system is ended.

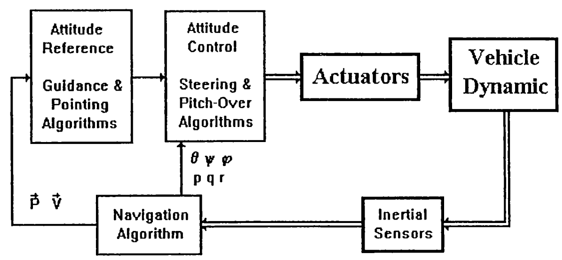

Fig. 2 - General Block Diagram of VLS Control System

The navigation algorithm must operate during the whole controlled flight and it can be considered as part of the inertial measurement system. It relates a sequence of mathematical calculations that, starting from the variables measured by the sensors, estimates the inertial linear position and velocity of the vehicle besides supplying the attitude and angular rates values, compensated by its error models. These data are necessary for all the loops.

3. ALGORITHMS DEFINITION AND CHRONOLOGY

The several algorithms and loops that compose the control system are implemented in the on-board computer. It is necessary to describe them functionally, with its inter-relationships, interfaces and the chronology connected to the sequence of events. Then, it is defined the structure to be implemented in the on-board software, allowing to make it in a modular way.

The sequence, in that the several algorithms and control loops must be executed, is connected to the sequence of events of the vehicle (fig. 1) and it is shown in the figure 3. As described, previously, the control complex has[3] four loops and two algorithms, which are:
Navigation Algorithm - **NAVEG**;
Pointing Algorithm - **APONT**;
Attitude Control using Movable Nozzle - **TM1, 2** and **3**;
Roll Control using Liquid thruster - **ROLL**;
Pitch-Over Control using Cold Gas thruster - **BASC** and Guidance Loop - **GUIA**.

The evolution of the VLS project, brought new needs and restrictions to the conception shown in the original project. Besides, the initialization of the inertial measurement unit IMU requires a suitable algorithm for its accomplishment. Those new requirements were added to safe modes - calculation alternatives when the measurements show great differences in comparison to the expected values. Hence, some algorithms were separated increasing its complexity.

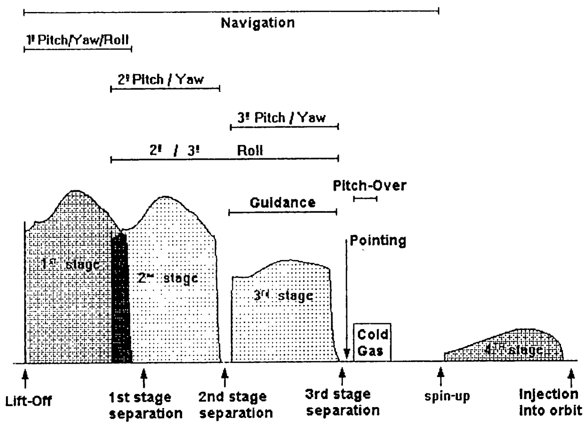

Fig. 3 - Sequence of Execution of the Control Loops and Algorithms

Figure 4 shows the chronology of all the algorithms execution, from the preparation for the flight up to the spin-up, when the work of the control system is finished. The dashed vertical lines mark the main events related to the algorithm chronology. Inside of some algorithms (TM2, TM3 and ROLL) different tables of coefficients are used by the same algorithm, having, therefore, in its chronology just changes in those tables. Inside of a same function (example: attitude control of the pitch angle) it is considered algorithm change when there is change in the controller's mathematical structure (BASC 1, 2, 3 and 4) or when different actuators are working (TM1, TM12 - 1° and 2° stages working simultaneously, TM2, TM3). Therefore, it is identified twelve algorithms to be operated during the flight: NAVEG, TM1, TM12, TM2, TM3, GUIA, APONT, BASC1, BASC2, BASC3, BASC4 and ROLL. All these are executed by the on-board computer.

The IMU initialization algorithm is executed partially by the on-board computer and partially by the Control Ground System that commands all the preparation of the vehicle for flight. The PASS algorithm is not for calculation, but for an initialization of parameters and inputs, in other words, it transmits the necessary information to the operation of the other algorithms, from the Control Ground System to the on-board computer RAM.

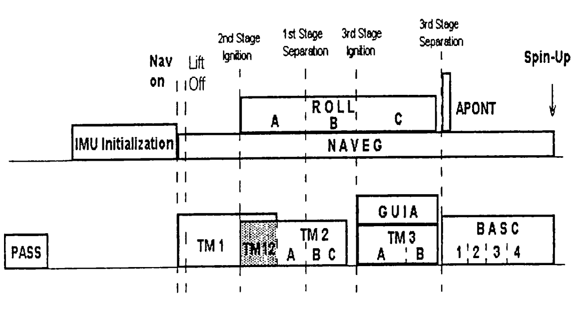

Fig. 4 - Sequence of the Algorithms

The adopted strategy is to store the whole mathematical structure of the algorithms and its relationships in the fixed memory of the computer (EPROM). All the coefficients of those algorithms and the reference attitude profile are transmitted, through PASS into the work memory, few minutes before the lift-off. This strategy allows to change parameters of the control system, besides its reference trajectory even with the vehicle ready to launch. Thus, the VLS Control System adapts for all the possible vehicle missions as well as to small modifications in the own vehicle.

4. CONTROLLERS DESCRIPTION

NAVEG - It is the algorithm that accomplishes the navigation of the vehicle, in other words, it uses the measures of the IMU to obtain the inertial position and the inertial velocity of the vehicle, besides its Euler angles and angular rates in the body frame. NAVEG begins with the command NAV-ON (approximately 5 seconds before the lift-off) and it only finishes with the command of separation of the equipment bay. NAVEG must be the first algorithm to be executed inside of each duty cycle of the on-board computer, because it supplies information to the other algorithms to be executed in the same cycle. Your functions are:

- to compensate the angular drift of the measures provided by IMU and to provide the Euler angles between the vehicle and the Navigation frame;
- to calculate inertial linear position and velocity of the vehicle in the Navigation frame; and
- to calculate the instantaneous specific force to be used in the sequence of events.

TM's - The algorithms TM1, TM12, TM2 and TM3 use movable nozzles control actuator for each stage, respectively. The design structure[4], therefore, is the same. The figure 5 shows the block diagram of this structure (P.I.D. controller) with notch-filters for the stabilization of the vehicle bending modes. However, they are considered as different algorithms since they use physically different actuators. Basically, the differences among those algorithms are in the tables of coefficients (fig. 6). the variation of those coefficients, inside of each table, it is due to the use of the gain schedule technique, and among different tables it is due to the big physical changes suffered by the vehicle when staging. Its functions are:

TM1 – Pitch, Yaw and Roll attitude control. Roll control is done by deflection of the four movable nozzles of the first stage. TM1 receives as initialization of PASS the tables PY1, R1, FILTRO1 and the reference attitude profile of the nominal trajectory.

TM12 - Pitch, Yaw and Roll attitude control using the same actuators of the first stage added to the use of the nozzle of the second stage in two perpendicular movements to each other. TM12 receives as initialization of PASS the tables PY12A, K1K2 (regarding the weighting of the command to be shared among the actuators of the first and of the second stages), besides the previous tables.

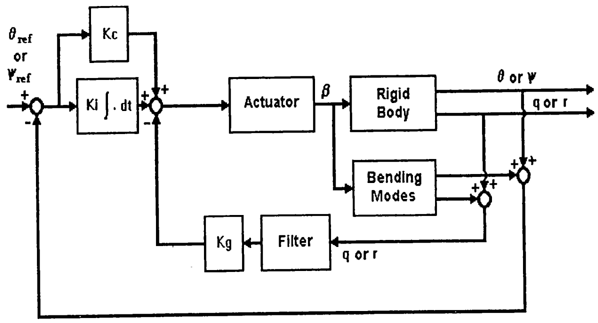

Fig. 5 – Block Diagram of the Controller TM

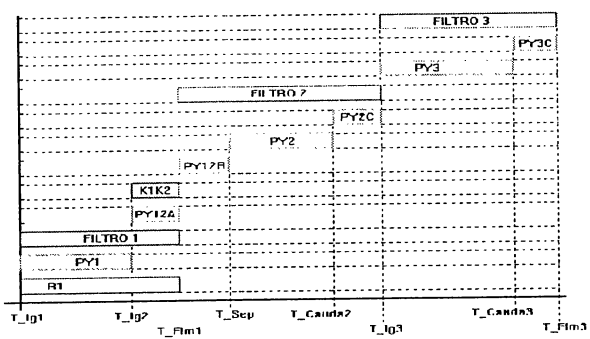

Fig. 6 – Tables of the TM's Coefficients

TM2 – Pitch and Yaw attitude control using the movable nozzle of the second stage (in two perpendicular movements to each other) after the first stage burning end. TM2 receives as initialization of PASS the tables PY12B, PY2, PY2C, FILTRO2 besides the attitude profile.

TM3 - Pitch and Yaw attitude control using the movable nozzle of the third stage (in two perpendicular movements to each other) after the separation of the second stage. TM3 receives as initialization of PASS the tables PY3, PY3C and FILTRO3. The attitude profile comes from the guidance algorithm GUIA.

GUIA - GUIA algorithm has as function the guidance[5] of the third stage of VLS. This means that, based on the instantaneous conditions of flight and of the final objective to be reached in the satellite orbit, the attitude profile that the vehicle should accomplish is obtained. Based on the energy conditions of the vehicle, GUIA can decide for a new objective for the satellite, in case the nominal objective is not possible to be reached. Its initialization needs only four parameters regarding the mass and thrust of the third stage.

ROLL - ROLL algorithm has as function[6] the control of the roll angle during the second and third stage, by using auxiliary thrusters. It receives from PASS the tables A, B and C. As this controller has, basically the regulator function and the actuators are On-Off type, ROLL will work those actuators only in case the roll angle is out of a range of acceptable values.

APONT - It has as function, based on the navigation data, to calculate the ignition time of the fourth stage and its attitude[6,7], for the satellite to enter in a possible orbit. That attitude will be the reference of the algorithms BASC, while the time of ignition determines, also, when it should be initiate the pitch-over movement and the instant in that the fourth stage should already be pointed in the correct direction. For its accomplishment, it receives from the PASS information of the velocity impulsive increment given by the motor of the fourth stage and its burning time. APONT foresees safe modes, in case of lack of energy to the satellization in a circular orbit. The alternatives are the ignition in the apogee of the path or an orbit that it begins in its perigee. In both cases a minimum of eccentricity is looked for.

BASC's - The algorithms BASC provide the pitch-over movement to point the fourth stage to injection in orbit. They are different algorithms because they have different functions, although they use the same actuators (cold gas thrusters). Figure 7 shows the block diagrams of the four algorithms BASC[8].

BASC1 - It has as function to stop the residual movement of the fourth stage, after the separation of the third stage. So, BASC1 controls the angular rate taking it inside of acceptable residual values.

BASC2 – It has as function to take, in minimum time, the roll angle of the fourth stage to a new value, calculated in the beginning of that algorithm. This positioning will allow that the pitch-over to be executed by BASC3, can be made inside of the plan of the actuators, minimizing the coupling during the maneuver.

BASC3 – It has as function pitch-over, in minimum time, the fourth stage of VLS in the direction defined by the current position and the inercial direction calculated by APONT.

BASC4 – It has as function to maintain the angles of Euler obtained at the end of BASC3, up to the instant of separation of the equipment bay - when the action of the control system is ended.

5. FINAL COMMENTS

The design techniques and analysis used in the VLS control system were quite modern and advanced. Many innovations in the little solutions of the problems that appeared, they did of the conception of the system as a whole, an original design and of high technical qualification. Its quality was demonstrated by the acting of the first flight, that in spite of anomalous (one of the four boosters didn't start), doing with that the vehicle flew stable and in the foreseen path.

Flight simulation and hardware in the loop simulation has been applied[8] for the design, analysis and verification of the control complex. The evaluation of the flight results (even partially) exhibits the excellent overall performance of the system even under unusual flight perturbations.

The design of the VLS Control System, here described, represents five years of the arduous work of a team of self-denying researchers that gave their best in order to make VLS as a vehicle of high technology. It was a great privilege to work with such team.

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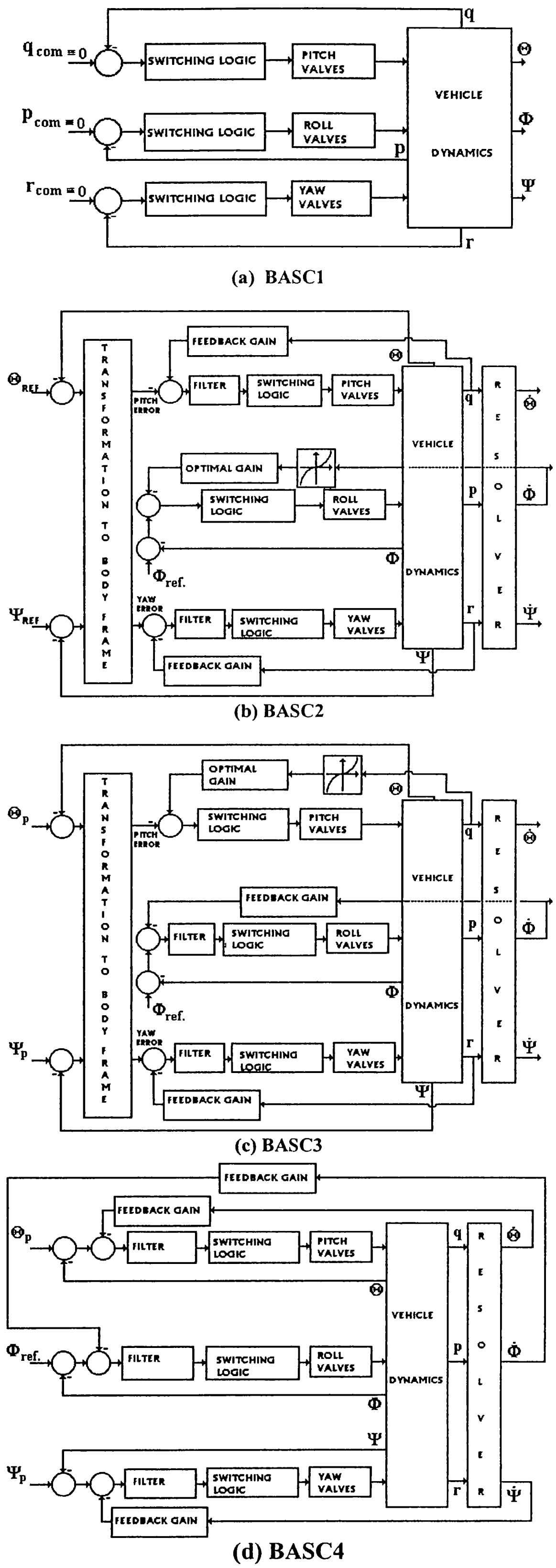

Fig. 7 – Block Diagrams of Controllers BASC