Robust Flight Control System Design Verification & Validation for Launchers

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This article presents the motivation, goals and benchmark problems of a study from the European Space Agency entitled "Robust Flight Control System Design Verification and Validation Framework" (RFCS). The objective of the study is to develop, demonstrate and compare the potential of modern control design, analysis and modeling techniques to address complex issues currently not well covered in the traditional launchers' verification and validation (V&V) process. The identification of these V&V gaps have resulted in a set of benchmark problems that allow comparing the standard results with those arising from the application of the advanced techniques. The benchmark problems are extracted from the VEGA launcher and its V&V process, but their significance is more general as they represent common issues found in most launchers.

I. Introduction

The current state-of-practice for launcher Verification & Validation (V&V) entails analysis of probabilistic time domain requirements, through nonlinear simulation Monte Carlo (MC) campaigns and/or nonlinear simulations using a set of selected worst-cases, as well as analysis of frequency domain requirements through a set of predefined vertex cases.

Although the MC approach is very practical in showing the design sensitiveness to parametric variations, it has many disadvantages in that it relies on massive amounts of computations without guaranteed proofs on the full parameter space. Indeed, the current V&V process suffers from inherent difficulties, such as discretization of the payload/flight-time, while most often times it results in overtly conservative results. For example, critical conservative results are obtained when the uncertain or time-varying system parameters must be considered uncorrelated due to the need to ensure worst-case margins over the full parameter scattering. To overcome these limitations many advances have been explored in the field of aeronautical and military GNC V&V based on advanced theories and tools[1,2,3].

Within the frame of a European Space Agency (ESA) study entitled "Robust Flight Control System Design Verification and Validation Framework" (RFCS) work is performed with the objective of developing, demonstrating and comparing with a traditional V&V framework a new enhanced design V&V framework through their application to the V&V of a complex launch vehicle.

This article presents the RFCS project, its goals and the benchmark problems (BPs) defined to address the most critical gaps identified in the current launcher V&V process. The compilation and presentation of these benchmark problems is critical to facilitate the introduction of modern analysis techniques into the current V&V process. The BPs are defined to allow any V&V engineer assessing the complexity of the task (i.e. the relevancy of the problem and of the model used) and to compare the outcome of the application of the advanced techniques to those obtained using classical approaches. This will serve the system-level experts to make an informed decision on introducing these techniques in the current launcher V&V process. The layout is as follows. Section II describes the RFCS project goals and objectives. Section III presents the VEGA launcher system and missions while Section IV details the benchmark problems used in the first phase of the RFCS project to verify and demonstrate the advantages of the considered advanced techniques.

II. The RFCS Project

A study entitled "Robust Flight Control System Design Verification and Validation Framework" (RFCS) is being funded by the European Space Agency (ESA) to address the known gaps in launchers' V&V. This study arose due to ESA's programmatic efforts to develop in Europe the next generation of launchers. The consortium is formed by Deimos Space S.L.U (lead, Spain), ELV (Italy), A3R (Italy) and DLR (Germany) with ample experience in launchers (i.e. ELV is the main contractor of the future European launcher VEGA[4, 5]) and advanced techniques[6, 7, 8].

The work in the frame of the RFCS project is aimed at developing an alternative framework for the design, validation and verification of LV control laws. Improvements will be made so as to reduce the time of the DVV task through the use of integrated tools, and to guarantee the coverage of the specifications in the full required domain.

The general objectives of RFCS are to develop, demonstrate and compare with a Traditional V&V Framework a new enhanced design V&V framework (EDV&VF) for launchers, in order to: (1) Better manage and increase robustness stability and performance robustness margins from the linear to the nonlinear case, from SISO to the MIMO case, by developing enhanced metrics; (2) To reduce the validation and verification gaps in the current launcher V&V; and (3) to significantly reduce the V&V effort by employing enhanced modeling, analysis and tuning concepts by using more intelligent and efficient optimization and worst-case analysis tools and to industrialize the most promising of them in order to be used in future ESA projects.

This objective is achieved by addressing the following secondary objectives: (i) Identification of technology gaps in the traditional DV&V framework being applied currently in industry; (ii) Definition and Specification of an Enhanced V&V Framework on the basis of a well understood interpretation of the peculiarities and criticalities of the selected launcher mission phases and of a well focused literature review; (iii) Detailed design, implementation and integration of the V&V techniques, supported by the existence of a set of benchmark problems that highlight the limitations of currently available Traditional Framework. Implementation and testing on study cases; (iv) To industrialize the Enhanced DV&V Benchmark through its application to a prototype DV&V process as currently conducted in the industrial setting; and (v) for the identified critical phases of the launch scenario demonstrate the effectiveness of the enhanced DV&V approaches in overcoming the difficulties encountered in the application of current Traditional DV&V method (Monte Carlo based), through a comparison between them.

The demonstration and comparison is to be performed through the application of the EDV&VF to the V&V of a complex launch vehicle, specifically the VEGA launcher. The proposed enhanced DV&V framework was presented in reference[9] and in what follows we detail the VEGA mission and more relevantly, the benchmark problems defined to address the identified gaps in the current V&V process.

III. The VEGA Launcher System and Mission

VEGA is the new European Small Launch Vehicle developed under the responsibility of ESA. The prime contractor for the launch vehicle is ELV. The launcher is entering the Qualification phase and the first launch is foreseen at the beginning of 2011 from the Centre Spatial Guyanais in Kourou.

The propulsion system of VEGA is composed of: three solid propellant motors (P80, Zefiro 23 and Zefiro 9) providing thrust for the 1st, 2nd and 3rd stages; and, a bi-propellant liquid engine (LPS) on the 4th stage (AVUM). The LPS can be re-ignited and performs up to 5 boosts. It is used for: transfer orbit injection (1st boost), scattering compensation, final orbit injection (2nd boost) and AVUM de-orbiting (last boost).

All four stages are controlled via a thrust vectoring system (TVC). The 4th stage also includes a Roll and Attitude Control System (RACS). During the propelled phase, the RACS system controls the roll rate while in ballistic phases it performs a three axes control. A strong constraint on the missions is the safety: the separated stages must fall on sea areas.

In the reference mission of VEGA, see Figure 1, a 1500 Kg payload will be released at 700 Km altitude on a circular Polar Earth Orbit (PEO). In the Qualification flight, a 700 Kg payload will be released at 1450 Km altitude circular orbit of 71 deg inclination. Since the payload (PL) masses range from 300 kg up to 2500 kg, the type of missions are manifold: equatorial, polar, SSO, multi-PL, barbeque mode in long ballistic phase and payload release with spin among others. Along the nominal trajectory, the flight parameters are subject to important - though predictable - variations versus time.

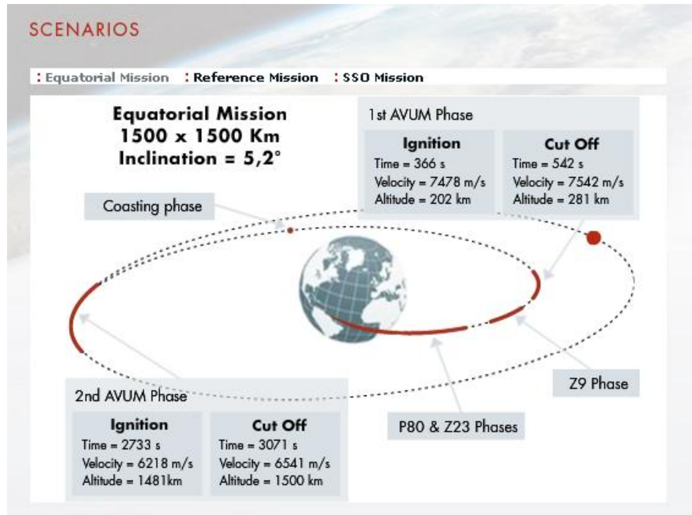

Figure 1 VEGA launcher and mission scenarios

IV. RFCS benchmark problems: a representation of traditional launcher V&V gaps

In this section the benchmark problems (BPs) defined within the RFCS project are described. These BPs represent the identification of gaps in the current launcher V&V process that are considered as necessary to be addressed. These gaps are nowadays circumvented with more exhaustive simulation and in-depth tailored investigations which require significant amounts of time from the analyst. The advantage of using advanced analysis techniques is as stated before in reducing the effort while increasing the coverage of the analysis.

The BPs selected, see Table 1, cover anything from roll coupling effects during atmospheric propulsive phases up to load constraint assessment in a full 6 degrees-of-freedom simulator and reaction attitude control system (RACS) stability and performance during exo-atmospheric phases.

Table 1 List of RFCS benchmark problems

Name	Description	Current V&V
BP-a	Roll coupling MIMO margins	The roll rate couples the yaw and pitch channels, but their associated controllers are designed in a SISO framework assuming de-coupled motion. Furthermore, the standard V&V approach also assumes a de-coupled approach considering the roll rate as a frozen parameter. More recently, and thanks to the symmetry of the yaw and pitch channels in the frame of a linear model, a simplified approach to robust stability has been considered by ELV[4] which has allowed to account for MIMO margins, generalizing the SISO low and high frequency gain and phase margins. But the approach is not general enough as it does not account for time-varying roll rates.
BP-b	Robustness of launcher control to payload and trajectories	The frequency validation of the control on each channel (SISO approach) is currently performed via Nichols plots from which the desired margins are deduced: low-frequency rigid gain/phase, high-frequency rigid gain, 1st mode phase, and upper-modes' gains. Currently, the Nichols plots are computed on a set of predefined worst or vertex cases. These result from combinations of parameters using their minimal and maximal values, selected on the basis of engineering know-how. Thus, the approach is inherently limited in scope (only a number of combinations are tested) and the result is conservative as the parameters' dependency is not taken into account.

BP-c	TVC stability for rapid time varying dynamics	Tail-off phases are common to Solid Rocket Motors since the engine cannot be cut off and the launcher must wait for the end of the combustion. This results in a thrust decrease from its steady-state down to zero in about ten or fifteen seconds. In addition, during the P80 phase the dynamic pressure highly decreases due to the exponential diminution of air density resulting in a highly non-stationary system in which parameters variation is of the same order of magnitude as some variables. The traditional verification is based on: (i) Frozen time Nichols for LTI models stability and (ii) Monte-Carlo simulations in time domain, which typically yield limited and conservative results.
BP-d	TVC robust stability to sloshing and payload	The TVC is typically designed for the rigid mode i.e. rotation around the center of mass of the launcher. In closed loop, the rigid mode must be stabilized (in atmospheric phase is unstable while in the exo-atmospheric phase is a double integrator). Additionally, in presence of sloshing modes, the launcher may lose stability. Thus, attention must be paid to deduce the stability of the system with sufficiently non-conservative margins to ensure against these modes. The traditional analysis is performed via linear theory and nonlinear simulations using a set of finite cases. This limits the coverage of the analysis.
BP-e	RACS stability & performance	The scope of this BP is to compute the frequency and amplitude of limit cycles (LC) of the reaction attitude control system (RACS) in ballistic phases. Typically, this is analyzed only via time domain simulations which are used to check: stability, number of activations, and absence of high-order modes coupling. Application of classical techniques is not straightforward since the system is on/off modulated.
BP-f	Load constraints assessment	The verification of general loads for a launcher is of high concern. The criteria for this verification are typically expressed in the time domain (e.g. as a maximal value of the product dynamic pressure by angle of attack computed over time) and cannot be foreseen during the design in frequency domain. In the traditional framework, the verification is done via Monte-Carlo simulations where each launcher parameter is scattered following a specific distribution (uniform, Gaussian, mixed). This approach is of course not optimal and cannot yield the domain of parameters that lead to the limit of the criteria violation. In addition, taking into account the presence of non-constant roll rates during atmospheric phases, another objective is to introduce its time-variation and coupling effect to calculate worst-cases in terms of the system stability.
BP-g	Capture	The scope is to analyze the Capture by TVC Control of initial conditions due to disturbances at stage separation. It is proposed to use, as for the tail-off analysis, Lyapunov based methods to demonstrate stability of a time variant and nonlinear system. The system is in essence nonlinear due to the saturations in deflection angle and rate. Nevertheless it could be considered as piecewise linear model (PWL). The main point is to manage the stability margins and the time of response to recover the initial conditions in a duration less than Tmax (typically 5s).

A. BP-a: Roll coupling MIMO margins

For low roll rates and because of the vehicle axial symmetry, the small-amplitude pitch, yaw and roll motions can be regarded as being virtually decoupled. This is the reason why, for this class of launch vehicles, the TVC control laws applicable to the pitch and yaw axis are identical and their design is based on a decoupled model. Even so, during the Design Verification and Validation (DV&V) phase the fully roll-coupled pitch/yaw dynamics must be addressed. The current approach is to assume frozen values of the roll for the coupled motion and obtain its stability margins. Thus, the scope of this BP is to extend the current approach to quantify the effect of roll coupling on the MIMO pitch/yaw channels stability margins to the bounded uncertain/time varying parameter cases.

The model used is a linear time invariant model of the LV obtained along the selected reference trajectory. In the context of this BP it is desired to analyze roll coupling stability during the P80 phase of flight, under the assumption of pure rigid-body dynamics. During this phase the launcher is propelled through the atmosphere under the thrust provided by its P80 solid-rocket engine and is characterized by strong aerodynamic forces acting on a relatively rigid system. Thus, the LV coupled pitch/yaw rigid body motion dynamics is completely described by its pitch and yaw attitude (θ and ψ) and linear motion (y and z) in a frame linked to the velocity of the reference trajectory.

Under the assumption of a perfect axial-symmetric launch vehicle, the three dimensional small-amplitude motion of a rigid LV can be completely described by linearizing Newton's law, Euler's equations and Euler's angle kinematics. The system state gathers pitch (q) and yaw (r) rates, heading (ψ) and pitch attitude (θ) Euler's angles, and the LV linear motion in the yaw and pitch directions (*zdot*, *ydot*, *z*, *y*). The system inputs are the commanded TVC deflections in the pitch and yaw directions ($\beta_{\psi c}$, $\beta_{\theta\, c}$). Once the desired linearization point is selected, such a state space system thus depends parametrically only on roll rate.

Two study cases should be covered: the first one focusing on the effect of the roll rate while the second considering that the instability coefficient A_6 and the controllability coefficient k_1 as uncertain parameters. In both cases, the roll rate should be assumed first as an uncertain (static) parameter of known range, and subsequently as a true time-varying parameter. Also, to exemplify the approach, the model is considered initially for a single point along the trajectory but afterwards it should consider the true time-varying plant (using a family of LTI plants at different time instances).

B. BP-b: robustness of launcher control to payload and trajectories

The first stage, or P80 phase, of the VEGA launcher is characterized by many uncertain parameters to which the control system needs to be robust. The current approach to controller validation is very time consuming and based on the frequency validation of the control on each channel. This validation is currently performed via Nichols plots from which the desired margins are deduced: Low-Frequency Gain Margin (LFGM), High-Frequency Gain Margin (HFGM) and Delay Margin (DM). The Nichols plots are computed on a set of predefined worst cases which constitute a subset of all the Vertex cases and have been obtained through engineering know-how.

An Enhanced framework must ensure that the margins are valid on a whole domain of data:

- Range of payload masses (introducing a dependence of inertial and elastic data versus the PL mass),
- Time intervals (proving the tuning for all instants and not only on a sample of instants),
- The entire scattering domain (and not only the vertices).

Furthermore, it is desirable to reduce the conservative level by introducing correlations between parameters (this technique is already partially adopted in the traditional framework by introducing a correlation between dynamic pressure and thrust). It is also desirable to be able to correlate each uncertain parameter with respect to the scheduling parameter (non gravitational velocity), so as to have a model which is valid for various flight regimes.

The Launch Vehicle (LV) model should include as a minimum the rigid and bending modes but also the TVC model. The scheduling variable for the model is the Non Gravitational Velocity (NGV) in steady-state and the longitudinal acceleration in tail off phase. The sloshing modes will not be considered in this analysis. Thus, the LV model for this BP is based on the linearized dynamics of the launcher given in second-order form and including two flexible modes. An affine model of the uncertain system for the LV in P80 phase near max dynamic pressure is given dependent on 14 uncertain parameters (from angle of attack to axial aerodynamic coefficient and MCI properties) based on a set of correlated data representing the flight domain.

C. BP-c: TVC stability for rapid time varying dynamics

The scope is to demonstrate the robust stability of the launch vehicle's thrust vector control (TVC) in the face of rapid time varying dynamics such as those occurring during tail-off phases. Tail-off is characterized by an abrupt decrease of the engines' thrust from its steady state value to zero. Additionally, when the LV is inside the atmosphere the open-loop plant turns into a highly non-stationary system where parameters variation is in the same order of magnitude as some variables.

The traditional verification is based on (i) frozen-time Nichols for linear time invariant (LTI) models stability and (ii) Monte-Carlo simulations in time domain. This approach yields limited and conservative results since in the former analysis the time variability cannot be taken into account, and in the latter only a finite set of conditions are tested.

It is desirable that the approach be enhanced to directly account for the time-varying dynamics in an analytical setting, e.g. through the use of integral quadratic constraints (IQC) or Lyapunov functions. In this manner non-conservative stability margins could be deduced. Thus, the tasks proposed are to:

- Demonstrate the system stability with the current TVC law (gains, filters, and adaptation law) in the face of time-varying dynamics.

  And if necessary, approximate the time evolution of the variables in tail-off by analytical formulae (for example polynomial versus time). Similarly, the scheduling of the TVC gains/filters/adaptation could be analytically approximated.

- Find if other TVC adaptation laws can be proposed.

To reflect the different (endo and exo atmospheric) situations, two phases are to be analyzed:

- The first analysis focuses on Z9 tail-off, an exo-atmospheric phase where bending modes are at a rather high frequency and all gain controlled. To analyze this phase, a simple rigid body model of the LV's yaw attitude dynamics can be used.

- The second analysis focuses on P80 tail-off. This analysis is more complex, because the tail-off occurs in the atmosphere and the role played by bending modes cannot be underestimated. To analyze this phase, a dynamic model of the system, including elastic modes needs to be analyzed.

The model used is similar to that from BP-a but tailored for each of the two selected phases. The main difference being that for the Z9 phase, both the instability coefficient A_6 and lift force coefficient a are assumed to be identically zero.

D. BP-d: TVC robust stability to sloshing and payload

As mentioned in BP-a, the TVC control laws applicable to the pitch and yaw axis are identical and their design is based on a decoupled model of the rigid motion, i.e. rotation around the center of mass of the launcher. In closed loop, the rigid mode must be stabilized (in atmospheric phase, it is unstable and in the exo-atmospheric phase is a double integrator). But, since the domain of payloads generates a domain of rigid mode characteristics (global mass, centre of mass and inertia) it is necessary to assess the robust stability for the entire domain of payloads. In addition, the payload is also assumed to have sloshing depending of its mass and the tank geometry. The presence of sloshing modes is also known to destabilize the system, thus attention must be also paid to provide these modes with sufficient margins. This fact is reflected in technical specification and performed via linear analysis.

In the traditional DVV framework, a number of test cases (e.g. several dozen) is defined to cover the payload domain. In the enhanced framework, it would be desirable to define analytically the set of payloads and demonstrate the compliance (in terms of stability and robustness) analytically. Thus, the scope of this BP is to validate the control law over a full domain of payloads and including sloshing effects.

For this BP, the (yaw) rigid body motion is planar and completely described by its yaw attitude θ and linear motion y (taking place in a direction transversal to the projection of the velocity vector in the pitch/roll plane) in a frame linked to the velocity of the reference trajectory. Transversal accelerations (in the y direction) cause the fuel stocked in the payload's tanks to slosh. Depending on its frequency and magnitude, this motion can significantly deteriorate the system's performance, to the point of threatening to destabilize the system. Note that only sloshing due to payload needs be considered, because the rocket engines' fuel tanks are commonly equipped with suitable damping devices that effectively inhibit fuel sloshing.

With respect to the sloshing model, several are proposed in the literature but the most prominent are the spring-like and pendulum-like sloshing models. Such models describe the complex sloshing dynamics with a single mode representation where the whole sloshing mass is assumed to rigidly move, as if "frozen", in its tank. In this BP, a spring-like sloshing model is adopted, where the sloshing motion envisions a rigid motion of the fuel in the y direction (fuel slosh responding to cross accelerations). The effect of the sloshing mass on the system is then modeled as an elastic force responding to the fuel displacement in the y direction.

E. BP-e: RACS stability & performance

The scope of this BP is to compute the frequency and amplitude of limit cycles (LC) of the reaction attitude control system (RACS) in ballistic phases. Limit cycles are either:

- Desired (low frequency for rigid mode) and result in a trade-off between required accuracy on angle / angular-rate and hydrazine consumption / number of activations.
- To be avoided (high frequency behaviour) when resulting from bad tuning or resonance with structural or sloshing modes. This behaviour is called chattering.

The traditional approach relies on a simple model based on a double inertia in the phase plane (theta, theta dot) and leads to very simple and practical results (LC amplitude and frequency).

It is desirable to ensure that the results hold when the model is completed: actuator and sensor dynamics, sloshing modes, etcetera. Thus, it is proposed to define a method of prediction of limit cycles able to generalize the engineering results obtained so far. The objective will be to analyze, and if necessary optimize, the current RACS robustness and performance. Several enhancements to the traditional V&V approach are proposed:

- Consolidate theoretical aspects (stability of LC, non symmetrical oscillations),
- Analyze LC in presence of constant disturbing torque,
- Optimize, if necessary, the RACS tuning (K_P, K_D, *DTmin*) in function of the trade-off between the accuracy of angular control and the number of activations.

The model that can be used should focus in the Z-X plan (yaw) since the coupling between axes can be neglected in first approximation (motion is slow enough and gyroscopic torques are low, the body has a natural symmetry in terms of inertia and thrusters geometry). A very important point is the normalization of the model. The advantage is to be independent of numerical values of inertia, thrust and geometry. The analysis will thus be very generic (rather independent of payload and phase).

Thus, the body is modeled as a pure inertia: *theta'' = C/J*, where *C* is the commanded torque (*C=F*L*n* where *F* is the thrust level, *L* is the lever arm and n is the number of thrusters according to the axis) and *J* is the inertia. The control law is basically a proportional-derivative controller followed by a pulse-width-modulation (PWM) device since the RACS thrusters are commanded in on/off. The controller is characterized by two gains K_P (proportional) and K_D (derivative), by missionized data (estimated inertia, thrust and lever arm), by a sampling period *Tref* and by a PWM curve (typically a *DTmin* value equivalent to a dead zone and then a linear behaviour till the saturation to *Tref*). Thanks to the missionization data, the commanded torque is written as $J*(K_P*theta+K_D*theta')$ and then converted in commanded duration via an on-board thrust model *F* and lever arm *L*.

F. BP-f: Load constraints assessment

The scope of this BP is to assess the robustness of atmospheric control during atmospheric phase in terms of load constraints, which is a highly critical aspect for launchers. In addition,

The traditional approach uses a time domain criterion, based on the variable *Qa* (i.e. the product of the dynamic pressure by the total angle of attack), and applies a Monte Carlo campaign to obtain a probabilistic certificate on its satisfaction. This criterion cannot be addressed during the launcher frequency-domain design phase thus the validity of the design is completely ad hoc verified with the MC time domain campaign. Unfortunately, such campaigns require intensive computational resources and yield only a limited answer, i.e. whether the system violates or not the criterion for the finite set of cases tested.

It is desirable to search for worst cases in terms of the *Qa* criterion over flight time and with respect to the following parameters (i.e. degrees of freedom): gust altitude, MCI (mass, inertia and center-of-gravity), propulsion, atmospheric values, aerodynamic uncertainties, and TVC biases. Thus, it is proposed to use optimization-based approaches where the profile versus Mach not to be exceeded can be used as the target of the optimizer. For each Mach number, the result would be a set of scattering on parameters leading to reach the limit. There is not necessarily one solution to the problem, which is why it would be useful to give the domain of parameters leading to the limit of the criterion. A posteriori, a probability could be attached to this domain on parameters.

In addition, it is also desired to explore other cost functions, such as roll-rate deviations and/or acceleration limitations.

The model used is a 6 degrees-of-freedom nonlinear simulator of the VEGA launcher that is set up to perform simulations in the atmospheric flight phase P80, see Figure 2. This tool has been developed in Simulink with S-Function written in C-code and includes: the launcher vehicle model, the TVC, the GNC, the propulsion and MCI components, the INS and the aerodynamic model.

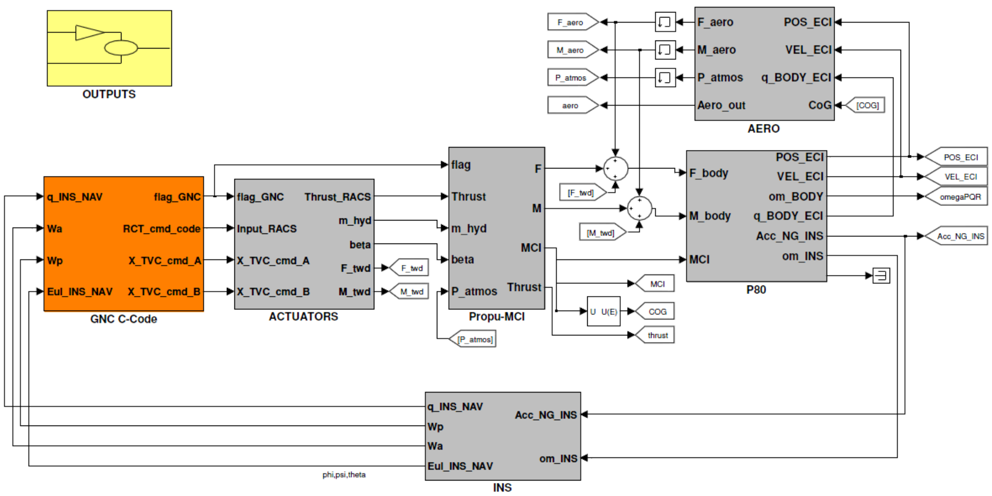

Figure 2 RFCS 6 degrees-of-freedom launcher simulator

G. BP-g: capture

The capturing phase is characterized by a set of manoeuvres as slew, spin, release, de-spin and CCAM. Therefore, it could be important a stability and performance analysis for a wide set of configurations. We consider the following model taking into account the rotational dynamics in a plane out of the atmosphere.

$$\begin{cases} \ddot{\psi}(t) = K_1(t)\beta(t) + a_s s + b_s \dot{s} \\ \ddot{s} = -\omega_s^2 \psi + (-\omega_s^2 + \lambda_1 a_s)s + (-2\xi_s\omega_s + \lambda_1 b_s)\dot{s} + (\lambda_1 K_1 + \lambda_2 K_3)\beta \end{cases} \tag{1}$$

The control law is a PD in attitude angle

$$\beta(t) = K_p \psi(t) + K_d \dot{\psi}(t) \tag{2}$$

Moreover, due to actuator device, saturations in angle and angular rate (β_{max}, βdot_{max}) are considered in (2). The dynamics of the actuators can be modeled by a second order transfer function.

The most straightforward mode of verification is the Monte-Carlo simulations for a given set of PL masses and scenarios. To be sure that assessment covers the desired domain, it would be helpful to employ optimization methods instead of Monte-Carlo. In parallel in order to demonstrate the compliance of the tuning (stability, number of activations and consumption) we would like to use analytical methods. The goal of this work is twofold:

- Robust stability;
- Robust performance in terms of the time of response to recover the initial conditions:
    - angle within 10% of initial condition
    - or angle within a value γ [deg]

As for tail off phase, the conditions are not stationary. The thrust is not instantaneously at its maximum value. In addition, the behavior can be nonlinear: if the initial conditions to be recovered are severe, the actuators saturations are easily encountered. They can lead to a succession of bang-bang commands if the gains are not well tuned with respect to the LV capabilities. Moreover the tuning of the PD gains is based on frequency domain analysis but in the same time, the time domain behavior is very important.

Since the analytical approach is difficult to be followed fully, it is proposed to consider Lyapunov based methods to demonstrate stability of a time variant system. The system is basically nonlinear due to the saturations in deflection angle and rate. Nevertheless it could be considered as a piecewise linear model (PWL)

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