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ESA CONTRACT REPORT

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**AURORA PROGRAMME
Planetary Ascent Vehicle**

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ABSTRACT
This document provides an executive summary of the analyses led in the frame of the AURORA PAV GNC study.

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1. INTRODUCTION

Within the frame of interplanetary missions, as considered by ESA/ESTEC in the AURORA exploratory program, the recovery of either a Mars soil sample collected by a robotic mission, or a crew in the frame of a manned mission, will require the master of the ascent phase from Mars ground. Thus, for both a Mars sample return mission and a Mars manned mission, the design of the ascent spacecraft shall enable the control of the trajectory in order to reach the objectives of the mission, while facing off-nominal flight conditions and before performing a cooperative (crew mission) or not (robotic mission) rendezvous with an orbiter on a circular orbit.

Thus, a dedicated study was the matter of the GNC for a Mars Ascent Vehicle. The objectives of this study were the design, development, test, and evaluation of the GNC of a Mars Sample Return and a Mars manned mission ascent vehicles. The emphasis was on the GNC system definition, algorithm and software development for these missions. It includes an analysis of the mission scenarios, the design of the vehicles with respect to GNC system, the design of their GNC algorithms and their benchmark using a non real time simulator and a real time test bench.

In this frame, different scenario options were studied, among which the altitude of the aimed orbit was traded for the two types of missions. From the retained scenarios, two spacecraft were in a first step roughly sized in terms of mass and propulsion features. Then, a complete design was performed, including the layout and the complete mass budget breakdown. A reference trajectory was built for the two missions, considering these design and scenarios.

GNC algorithms were designed for the two MAV configurations. At first, GNC requirements towards sensors and actuators were defined. Then, the design of each algorithm was derived from a trade-off analysis.

Besides, a complete and generic 6-dof functional environment simulation (FES) tool was developed, in order to provide a dedicated facility for running numerical simulations involving the selected GNC algorithms together with the designed MAV, for both sample return and manned missions.

Moreover, a Real-Time Test Bench was developed (on the basis of existing ATPE platform), with the auto-coded models derived from the FES and the GNC algorithms coded in C.

At the end, the overall GNC assessment was based on simulations performed on the FES (by the mean of unitary worst cases as well as Monte-Carlo simulations) and on the RTTB (by the mean of dedicated unitary cases), thus providing GNC performance both by a statistical analysis and by real-time simulations.

All of the study objectives were fulfilled, in compliance with the Statement of Work.

The industrial organisation brought together experience in all technical fields required for the PAV GNC study:

- EADS Space Transportation SAS, acting as study Prime contractor,
- SciSys (Space & Defense) Ltd, responsible for the development of the FES,
- EADS Space Transportation GmbH, responsible for the development of the RTTB.

2. MISSION SCENARIOS & VEHICLE CONCEPT

The MAV objective is to give the access to space from Mars surface and to the return to Earth flight opportunity. Depending on the architecture of the overall mission, the target of the MAV ascent trajectory could range from a Low Mars Orbit (LMO) to a direct return to Earth hyperbola.

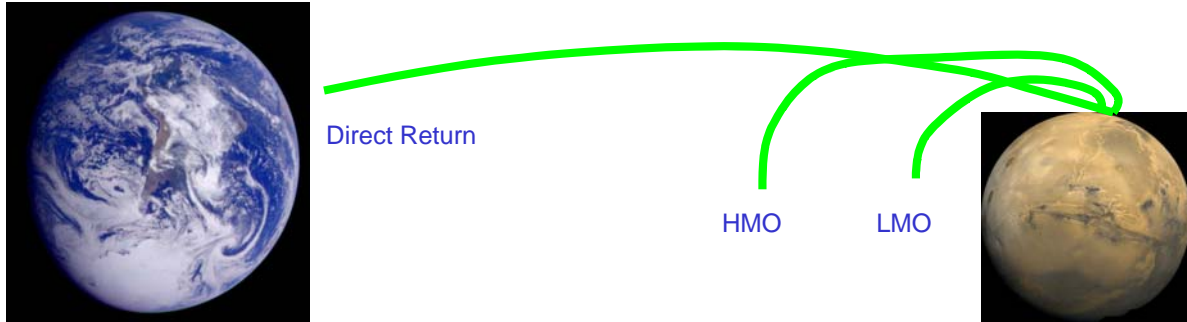


Figure 1 – Trajectory trade-off

Except in the case of a MAV flight directly targeting an Earth entry, the mission scenario involves a second vehicle, the Earth Return Vehicle (ERV), and a rendezvous between this one and the MAV upper part. The rendezvous itself can be performed in either LMO, HMO or interplanetary orbit.

The typical target LMO selected by the various studies is a circular orbit at an altitude of 400/500 km. The main reason of this choice is to reduce the mass budget of the MAV to the lightest possible value. The perigee altitude is set to a minimum value considering the residual drag and heat flux of the Mars atmosphere during the rendezvous process (resulting in a conservative value of 400/500 km) and the apogee altitude is set to the minimum value the get the minimum energy (circular orbit). Except for manned mission, this option leads logically to the design of MAV cooperation to the rendezvous reduced to its minimum.

The HMO option is justified by the purpose to reduce the task and the corresponding mass budget of the ERV to a value compatible with the design of sister ship vehicles of reasonable size at Earth orbit departure. This goal can only be reached by the development of a lightweight habitat module technology and by an aerocapture at Mars arrival. In this case, the MAV has to perform a first burn targeting the apo-axis, then a long duration ballistic phase, up to the apo-axis, and finally a second burn targeting the peri-axis. A typical figure for the MAV impulse budget is 5600 m/s.

The simplest interplanetary option would be to perform a direct return to Earth. It requires roughly a MAV propulsive ΔV of 7500 m/s, which leads to significantly increase the GLOW mass of the MAV. However, its main advantage is that it does not require any rendezvous anymore, such significantly increasing the reliability at overall mission level.

The main drivers of the MAV configuration are the mass of the payload and the targeted orbit, which both depends on the rendezvous option with the Earth return vehicle. In order to cover the maximum range of options, and taking into account the above considerations, the two following scenarios were considered as baseline:

- Robotic mission: circular LMO or 500 km, with a liquid propellant (MON/MMH) 2-stages MAV configuration, with a 4 kg payload mass,
- Manned mission: circular HMO or 15000 km, with a LOX-CH4 propellant one and half stage configuration, with 4 throttled and gimbaled engines.

3. VEHICLE DESIGN & ASCENT TRAJECTORY

The MAV for the robotic mission is a 2-stage launch vehicle with the upper stage nested inside the lower stage so as to minimise the height of the system and achieve compatibility with the DM lay-out requirements. The aimed orbit is a 500 km circular orbit, so the ΔV to be supplied by the MAV is about 4500 m/s.

The main propulsion system used on both stages is based on MMH/MON25 bi-propellant fuel with pressure-fed engines (off-the-shelf US RS21 engines were considered for both stages). Four engines are required for the first stage and one single for the second stage, in order to provide sufficient thrust: about $2 g_{0\text{Mars}}$ acceleration is required at lift-off, while $1.5 g_{0\text{Mars}}$ acceleration is required at 2nd stage ignition (so that gravity losses are minimised).

Controllability issues were considered for the lay-out definition, based on a flat configuration of the MAV, due to the Descent Module constraints. The obtained MAV configuration is:

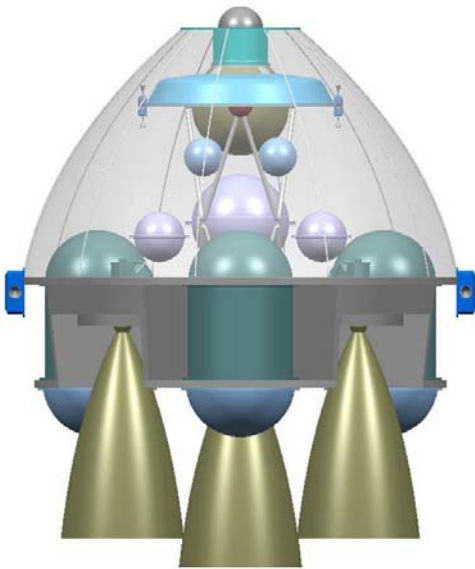


Figure 2a – MSR MAV : front view

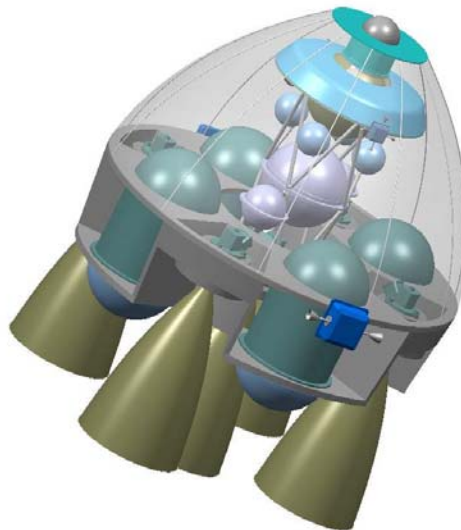


Figure 2b - MAV : isometric view



Figure 2c : 2nd stage view

The GLOW mass is 919 kg, including a propellant mass of 639 kg, and a budget for the 2nd stage of 81.8 kg. The trajectory of the robotic MAV is depicted hereafter (note that the

trajectory was constrained for controllability aspects with a limitation on the maximum product dynamic pressure x angle-of-attack):

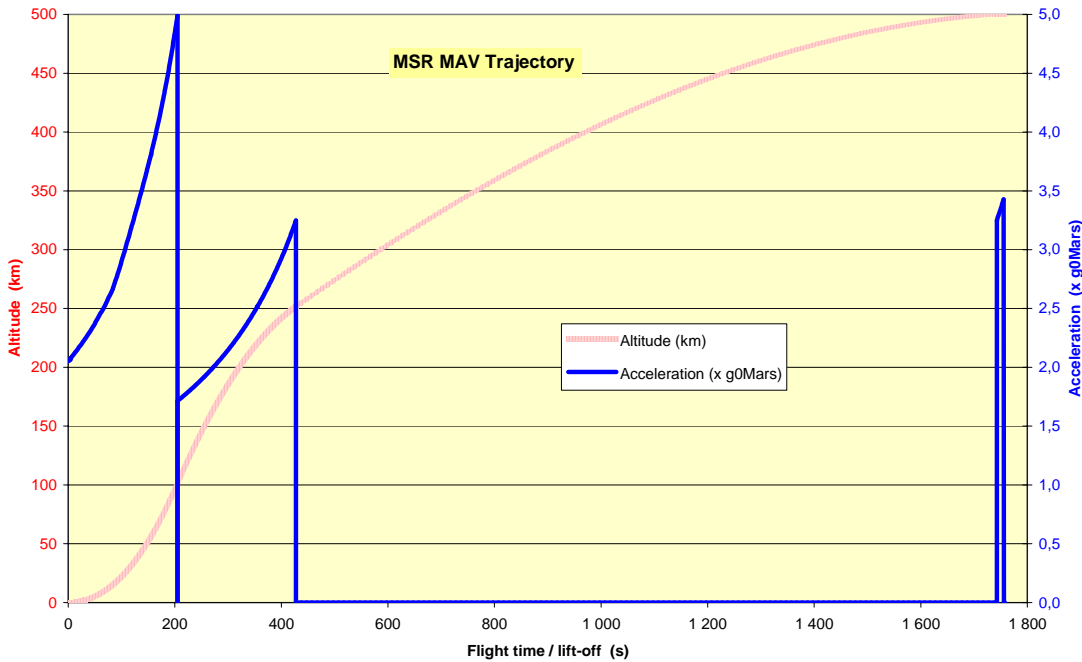


Figure 3 - MSR MAV Ascent trajectory

Concerning the Manned mission, the chosen MAV configuration is based on “one and a half” liquid stages with re-ignitable engines. The main purpose of this architecture is to keep the same main engines for the whole flight but to jettison a set of tanks when empty, thus limiting the overall dry mass. The launcher configuration is based on a conical capsule for the crew habitat, placed on top of the MAV. The aimed orbit is a 15000 km circular orbit, so the ΔV to be supplied by the MAV is 5520 m/s.

Thrust is assumed to be throttable: thrust modulation is used during the whole flight. The choice of in-situ propellant (LOX/CH₄) is adapted to a long-stay mission. Minimum thrust level is defined by the following constraints: 2 g_{0Mars} acceleration is required at lift-off, while 1.9 g_{0Mars} acceleration is required at 2nd stage ignition (so that gravity losses are minimised).

The obtained MAV configuration for the manned mission is:

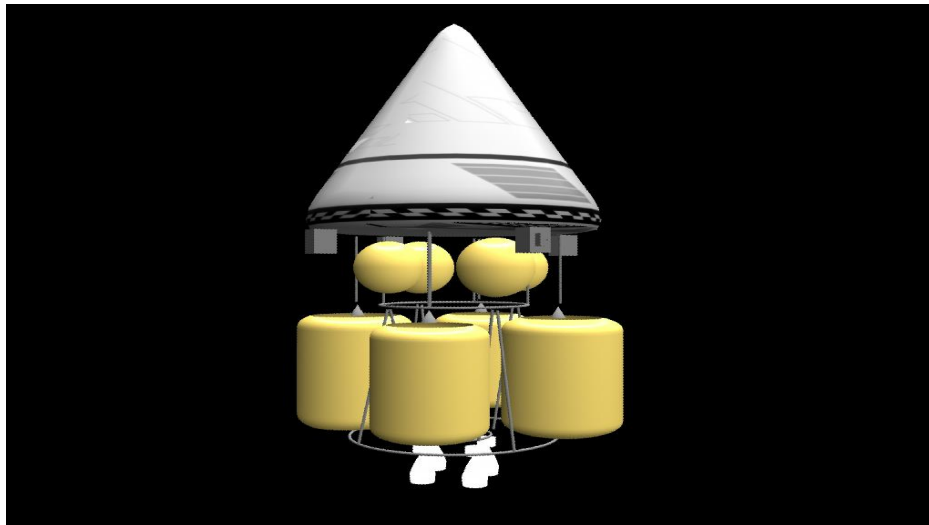


Figure 4 – Manned MAV view

One can notice the 2 sets of tanks: cylindrical for the lower stage flight, and spherical for the upper stage flight, and the cluster of four engines remaining during the whole flight.

The GLOW mass is 32 358 kg, including a propellant mass of 24 457 kg, and a payload mass (manned capsule) of 4800 kg. The trajectory of the manned MAV is depicted hereafter:

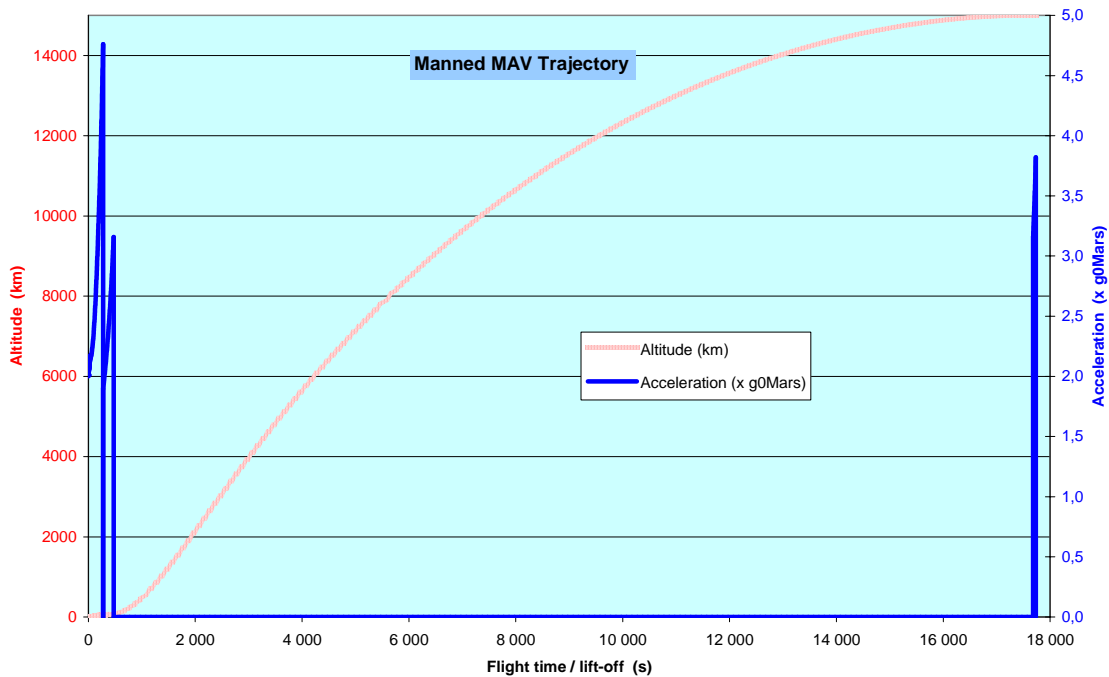


Figure 5 – Manned MAV Ascent Trajectory

4. GNC DESIGN

In order to define the GNC design, GNC requirements towards sensors (for the navigation) and actuators (for the control) were addressed in a first step, and then a trade-off has been performed for the GNC algorithms.

Navigation

With respect to an Earth ascent vehicle, the major difference comes from the uncertainties on the initial location of the vehicle. Earth launch pads are very accurately known but it is not the case for a MAV. A first estimate of the position can be extracted from the navigation of the lander at entry. This estimate can be refined by Earth or Mars orbiter measurements, during the mission on Mars ground.

Using a conventional inertial measurement unit with accelerometers and gyrometers, the autonomous alignment brings additional information on the latitude. The attitude initialization can be derived from the accelerometers information: a dedicated algorithm is able to estimate the local horizontal and azimuth, by filtering inertial measurements due to the gravity and to the planet rotation.

Besides, the advantage of using a star tracker was also addressed but it was not retained due to the added complexity compared to the low improvement in the attitude estimation accuracy.

Thus, in order to reach a good accuracy of the payload at injection into orbit, the retained configuration is based on a 0.01°/hour drift class-IMU (ATV-class could be acceptable for the MSR but not the manned mission which is quite long) and a launch pad offset less than or about a few kilometers (an initial position error much lower than 1 km is not required because from this level an improved accuracy has no effect on the injection accuracy). In such a case the MAV injection accuracy is good, for both robotic and manned missions.

The navigation algorithm itself is based on a classical Ariane5-like scheme, integrating the non-gravitational velocity increments provided by the IMU, taking into account the gravity thanks to an embedded gravity model (2nd degree / 2nd order model for Mars). During the coasting phase, the non-gravitational velocity increments from the IMU are not taken into account (the increments are set to 0), because they should be nil and only represent the IMU flaws.

Guidance

The guidance for the MAV shall bring the launcher onto the desired target (e.g. the aimed orbit) within a given accuracy, while minimizing the fuel consumption and ensuring that the path constraints are well met during the flight. Thus, the requirements are quite similar to those applied on a Earth launch vehicle.

For the MAV guidance three types of algorithms were considered: an implicit scheme based on a look-up table function of time or velocity, an adaptive scheme based on a bilinear tangent law (Ariane 4 like), and a predictor-corrector technique. The considered criteria for the choice of the algorithm were the performance and robustness on the one hand, and simplicity in the implementation on the other hand.

The three schemes were implemented and were tested within 3dof environment, and results were compared with a performance index defined as the correction cost (propulsive ΔV) to be provided by the payload once in orbit in order to correct the injection offsets.

For the robotic mission, the results are depicted on the following graph:

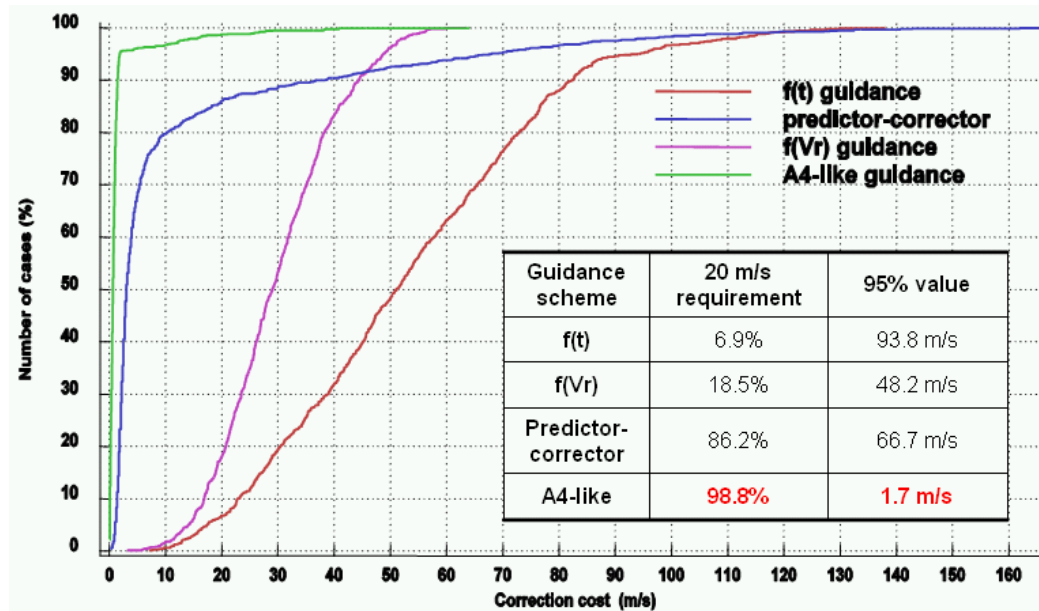


Figure 6 – Distribution in % of correction cost of the four guidance schemes

The open-loop algorithm based on pre-loaded tables versus either time or velocity, provides too poor injection accuracy with regard to the mission requirements. Both two other methods are based on closed loop algorithms able to compute at each guidance step a new optimal path with the target orbit as final objective and the fuel consumption as performance index. This was confirmed when adapting the algorithms to the manned mission.

Eventually, the retained guidance algorithm is the so-called “bilinear tangent law” scheme.

Control during propelled flight

During the propelled flight, the Control function consists in the elaboration of activation orders towards the actuators in order to meet the commands issued by the Guidance function, despite environmental perturbations and dispersions and uncertainties on the physical characteristics of the vehicle. The control function has to:

- Track the guidance orders (guidance vector) with specified accuracy,
- Provide a closed-loop stabilisation with specified performances,
- Keep the structural modes and propellant sloshing modes stable in closed loop,
- Take into account limited control resources such as limited forces and torques generation capacities, and sensor kinetics constraints.

At first, the different means used by the control function were analysed and traded, and requirements towards the actuators were derived, for the different envisaged propulsive architectures of the MAV.

The control logic is displayed hereunder:

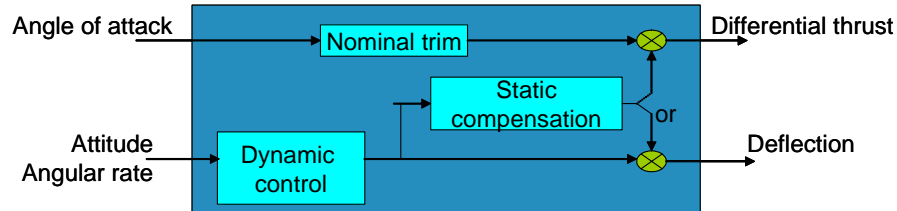


Figure 7 – Control Command Module Diagram

Then, the following most promising control concepts were benchmarked in the design for the MSR mission and the manned mission:

- Analytic modal control (simple and easy to implement),
- LQ control and related techniques (estimation and time-domain robustness),
- Multi-variable robust H_{∞} control (frequency-domain robustness).

	EA	LQG	H_{∞}
Advantages	It allows a direct application of response time requirements. It provides reduced order controller.	LQG methods are essentially time-domain methods. It allows achieving required performance, disturbance rejection or robustness specifications.	Closed loop internal stability is guaranteed. Robustness towards uncertainties and HF phenomena is insured. Performance objective can be taken into account through reuse of EA design
Drawbacks	Its main disadvantage is that it does not deal directly with uncertainties in models so that designs can guarantee stability performance and disturbance rejection	LQG methods do not deal directly with uncertainties in models. They need accurate models and the introduction of the estimator may fragilize the method. These methods may also result in high gain controllers.	The main disadvantage is the price paid for obtaining a direct solution : order of H_{∞} controller is directly related to the order of the weights

Figure 8 – Advantages & Drawbacks of the three Control concepts table

The results obtained on both stability analysis and performance were very close between those three algorithms, so the retained one was the analytic method simple design for both robotic and manned missions.

Next, stability margins and performance requirements have been checked for all cases, for both robotic and manned MAV. Thus, the control for the MAV, designed for the 3-axes attitude control during the 1st stage and for the pitch and yaw axes during the 2nd stage¹, is fully compliant with its requirements.

Control during coasting phases

During the coasting phases, the Control function consists in the elaboration of activation orders towards the attitude control system, composed of 2 pods of 3 on-off thrusters. Note that the same control is used for the roll control during the second stage flight. This function has then to ensure the MAV control, according to different modes associated to different kinds of manoeuvres:

- Slew manoeuvres, in order to orientate the MAV in a desired direction,
- Spin (resp. despin) manoeuvres, in order to provide a specified roll rate (resp. cancel the roll rate),
- Boost manoeuvres, for propellant settling before ignition purpose,
- Relaxed stabilised mode for long coasting phase, so as to minimise consumption and number of activations.

During the 2nd stage boosted flight phases, this function must also ensure the roll angle control, by balancing perturbation torques to keep constant attitude.

The control design choice was based on the following criteria: simplicity, computational burden, mission features (e.g. MCI approximately constant during coasting phase). A proportional – derivative control law for each axis was then designed, using an estimator of the attitude rates (based on a Kalman filter) and defining the commanded torque, eventually expressed in terms of commanded thrusters activations. Its scheme is depicted hereunder:

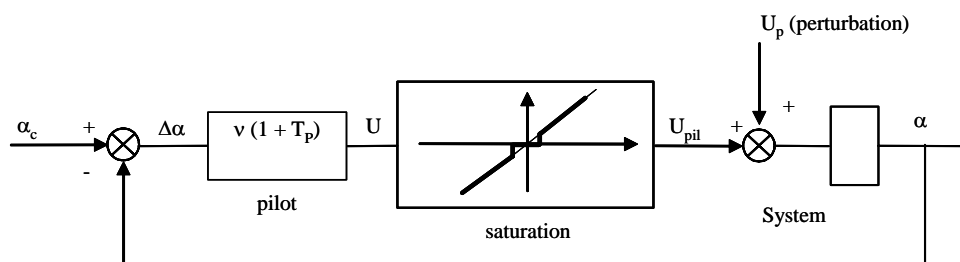


Figure 9 – Ballistic Control logic

Appropriate gain tuning was then performed for each specific mode, and the performance was assessed for both coasting phases and roll control during 2nd stage boosted flight, according to

¹ This split was defined according to the MAV architecture, in both robotic and manned configurations.

all the requirements in terms of attitude pointing and attitude rate accuracy, as well as considering realistic number of activations.

5. FES DEVELOPMENT

In order to assess the performance of the combined GNC, a specific non-real time simulator (so-called FES: Functional Engineering Simulator) was specified and developed. In order to take benefit from the previous ATPE works, the ATPE simulator based on MATLAB/SIMULINK platform was used as a basis.

This simulator represents the 6 degrees-of-freedom dynamics of the PAV from the lift-off up to the payload injection including the coasting phases and engines re-ignition capability on the considered planetary orbit for both missions: sample return mission and a manned mission. The Matlab/Simulink simulation tool consists of two parts: the simulation part, and the GNC part.

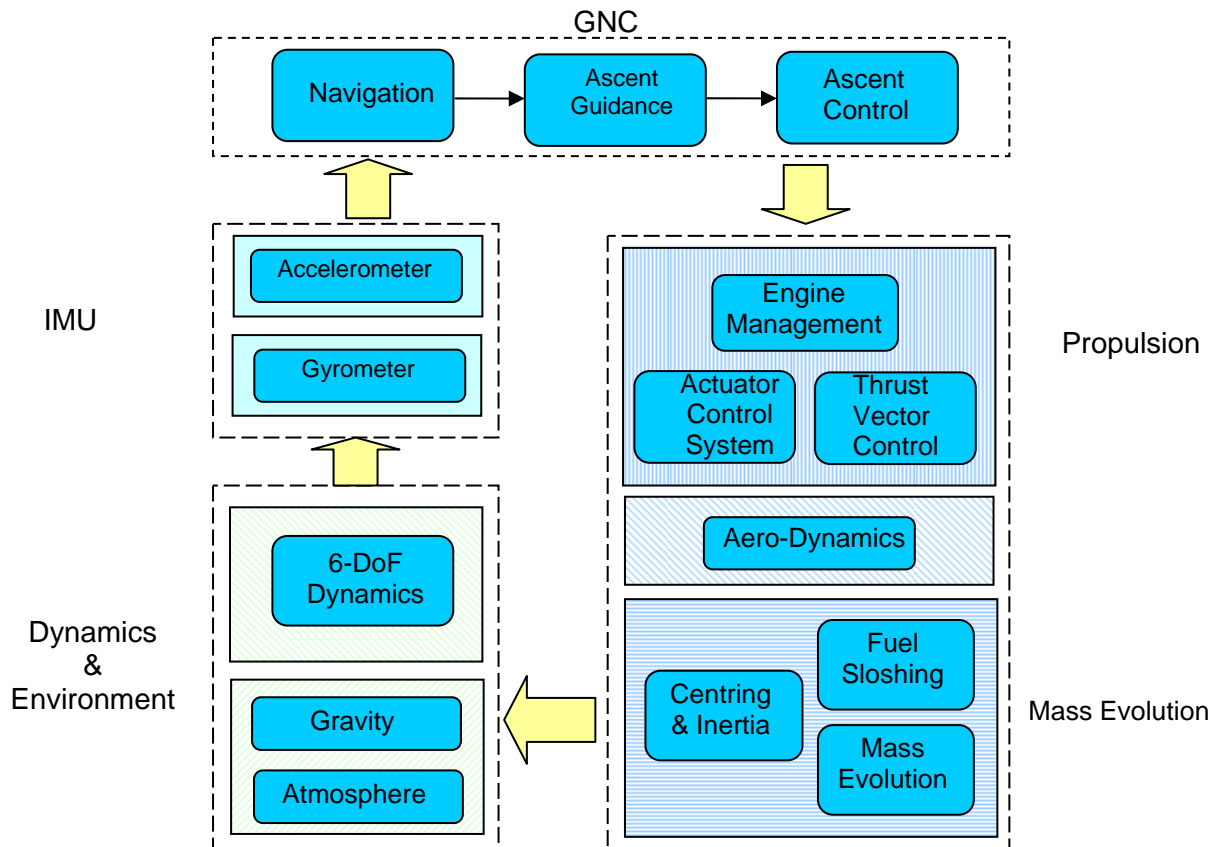


Figure 10 – Models Interconnection Logic

The simulation part simulates the dynamics of the launcher, environment, and planet, as well as sensor and actuators. The Simulator part is entirely coded in Matlab/Simulink in order to

allow an autocoding process to a real time environment. A graphical user interface is also be implemented. The PAV simulation tool has a Monte-Carlo capability for performance analysis of the GNC algorithms.

The main models developed or re-used from ATPE simulator are: Aerodynamics model, Main propulsion model , Mass evolution model, Centring & Inertia evolution model, TVC actuator model, ACS model, Sloshing model, IMU model, Disturbing torques model (separation, perturbing torques). Concerning the required models with regards to external environment, one has mainly: Mars gravity model and Mars atmosphere model (from EMCD including winds and gust). Eventually, a 6-dof dynamics model is used for integrating the MAV motion.

The GNC part contains the guidance, navigation, and control algorithms. To ensure the smooth migration to the real time test bench, the GNC part is coded in C, and inserted in Matlab/Simulink through a S-function interface. Requirements associated to the time execution of the simulations, or to the possible code adaptation with respect to the real time needs, were taking into account.

6. RTTB DEVELOPMENT

The performance assessment of the MAV GNC was even pushed further, by an evaluation within real-time environment, so called Real-Time Test Bench (RTTB). This bench consists of two parts.

The first part is a high performance COTS processor board (Motorola MVME5100 with a PowerPC 750 CPU) on which the GNC algorithms are integrated and executed.

The second part is a laptop computer. It hosts the Tornado host environment and the plant, i.e. the simulator issued thanks to the Matlab/Simulink autocoding process from the non real-time simulator. An initialization procedure was provided to overwrite autocoded parameters and allows validation runs with discrete dispersion and uncertainty values.

The two parts are connected via Ethernet and RS422 links.

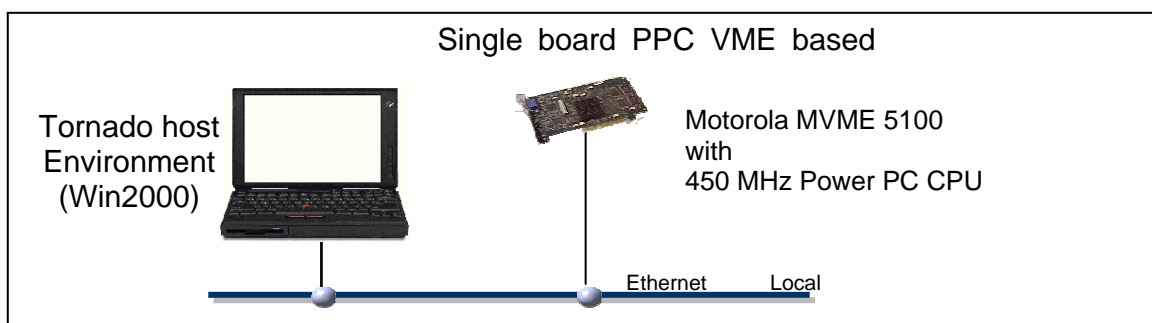


Figure 11 – Test Bench Implementation

A step-by-step verification process was performed in order to validate the RTTB, the main step was a full comparison of nominal cases with the non real-time simulator.

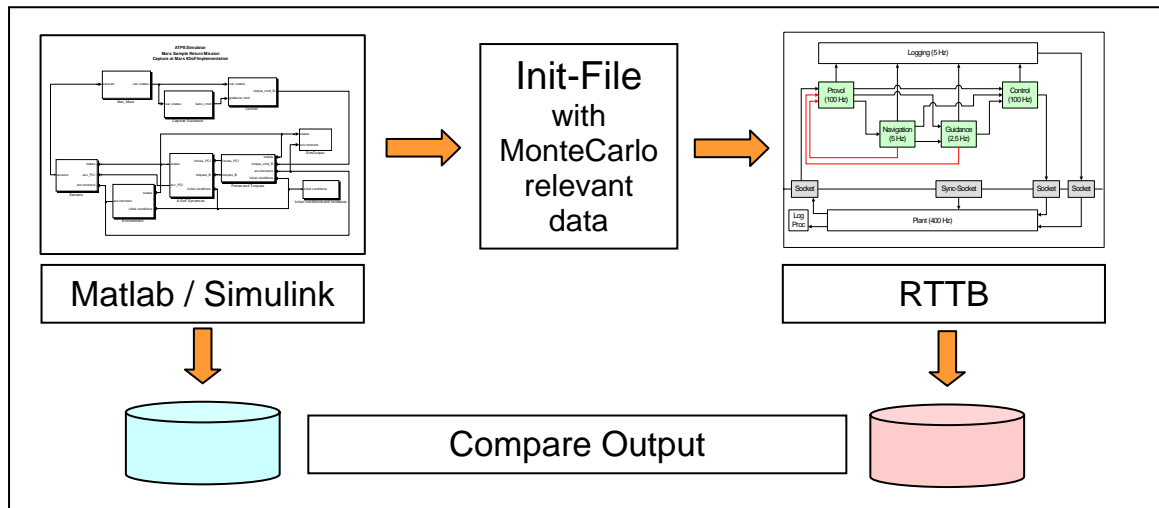


Figure 12 - Closed Loop Runs for Platforms comparison

7. GNC ASSESSMENT

Once the overall integration of GNC into the FES was validated, combined GNC performance was assessed. The non-real time validations objectives were:

- To validate the GNC architecture.
- To analyse coupling effects induced by algorithms integration (Navigation + Guidance + Control),
- To check GNC performances in a representative environment,
- To ensure smooth migration to the real time test bench.

In order to fulfil these goals, simulations were achieved considering specific mission scenarios such as:

- Nominal case,
- Cases with dispersions (PAV design, environment dispersions, equipment performances).
- Monte-Carlo simulations for Mars Sample Return (MSR) and Mars Manned Mission (MMM) were also be performed.

The results obtained showed that performances of each algorithm are kept after integration. No coupling effect was detected between algorithms. For the MSR MAV, offsets on semi-major axis do not exceed 7 km at 2σ , inclination 0.03843 deg, eccentricity 0.000928 and ascending node 0.1898 deg. These results are within the requirements deduced from unitary assessment.

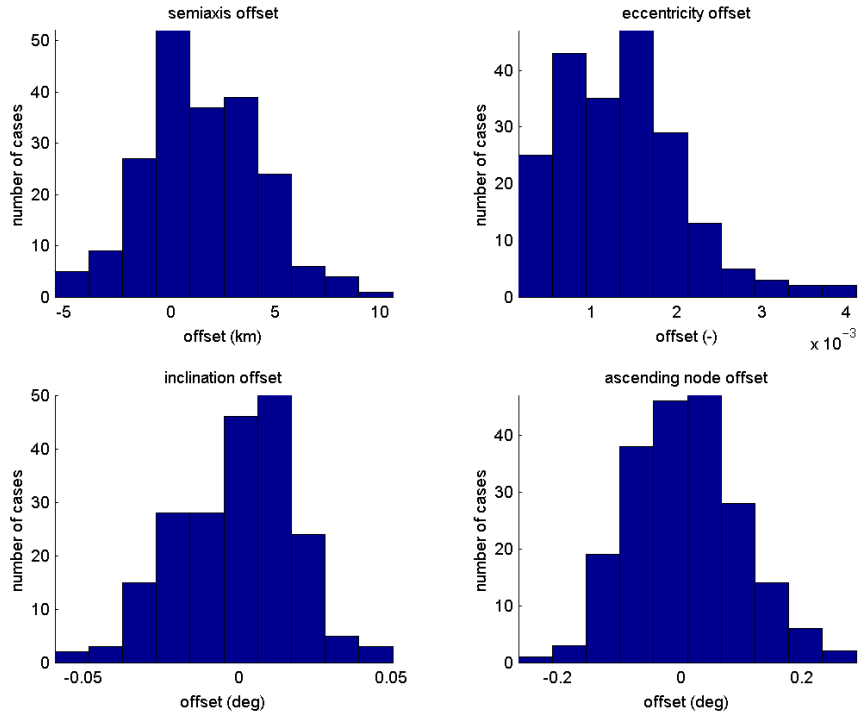


Figure 13 - Orbital parameters offsets at injection time (based on position and velocity given by the simulator: total error)

Moreover, as it is the case for Earth launcher, the main driver for those offsets is the navigation chain (e.g. IMU errors) while the own errors due to gnc algorithms remain very small.

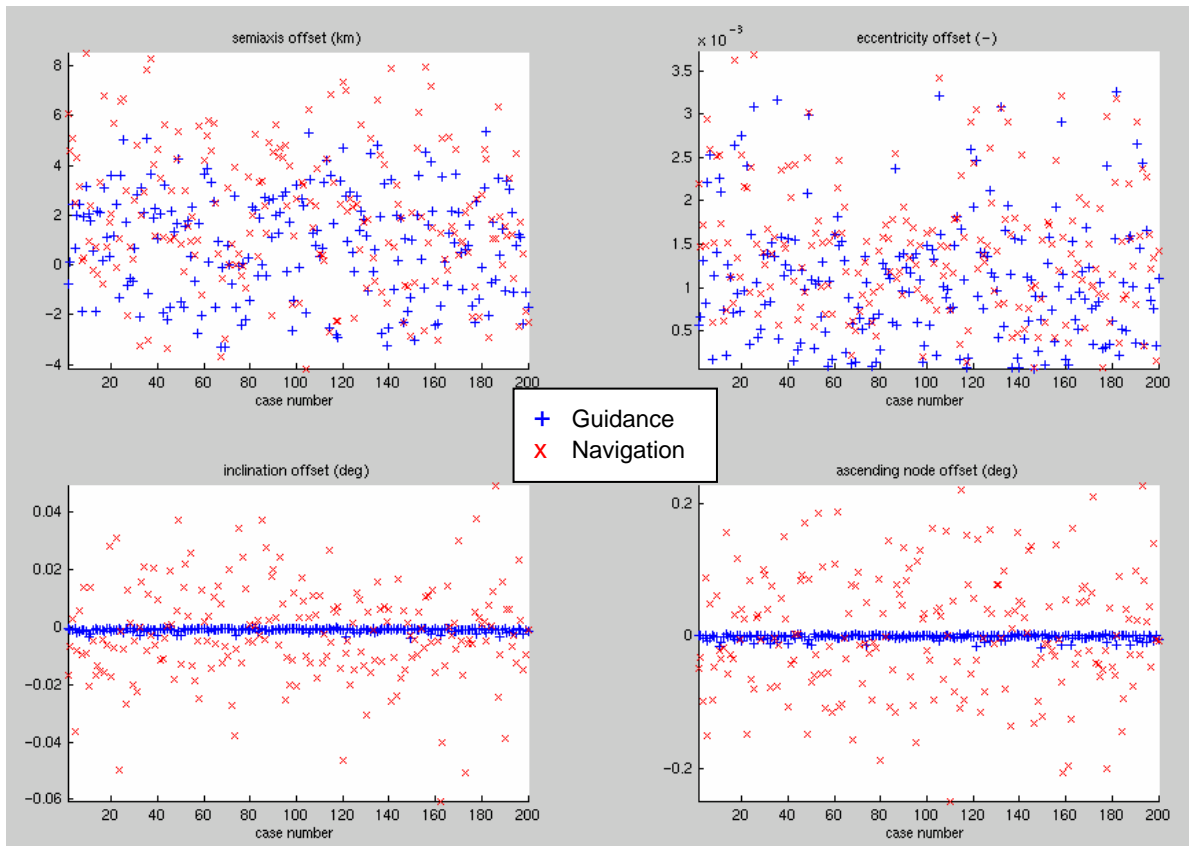


Figure 14 - Orbital parameters offsets at injection time (based on position and velocity given by the simulator: total error)

These results obtained through Monte-Carlo statistical analysis comforted the previous conclusions about the suitability of the defined GNC design to cope with the MAV mission. It also proved that the re-useability of MSR algorithms for Manned MAV mission only by the mean of data tuning.

Five cases on the RTTB confirmed that the GNC behaviour for the MAV is quite similar on FES and the RTTB platforms.

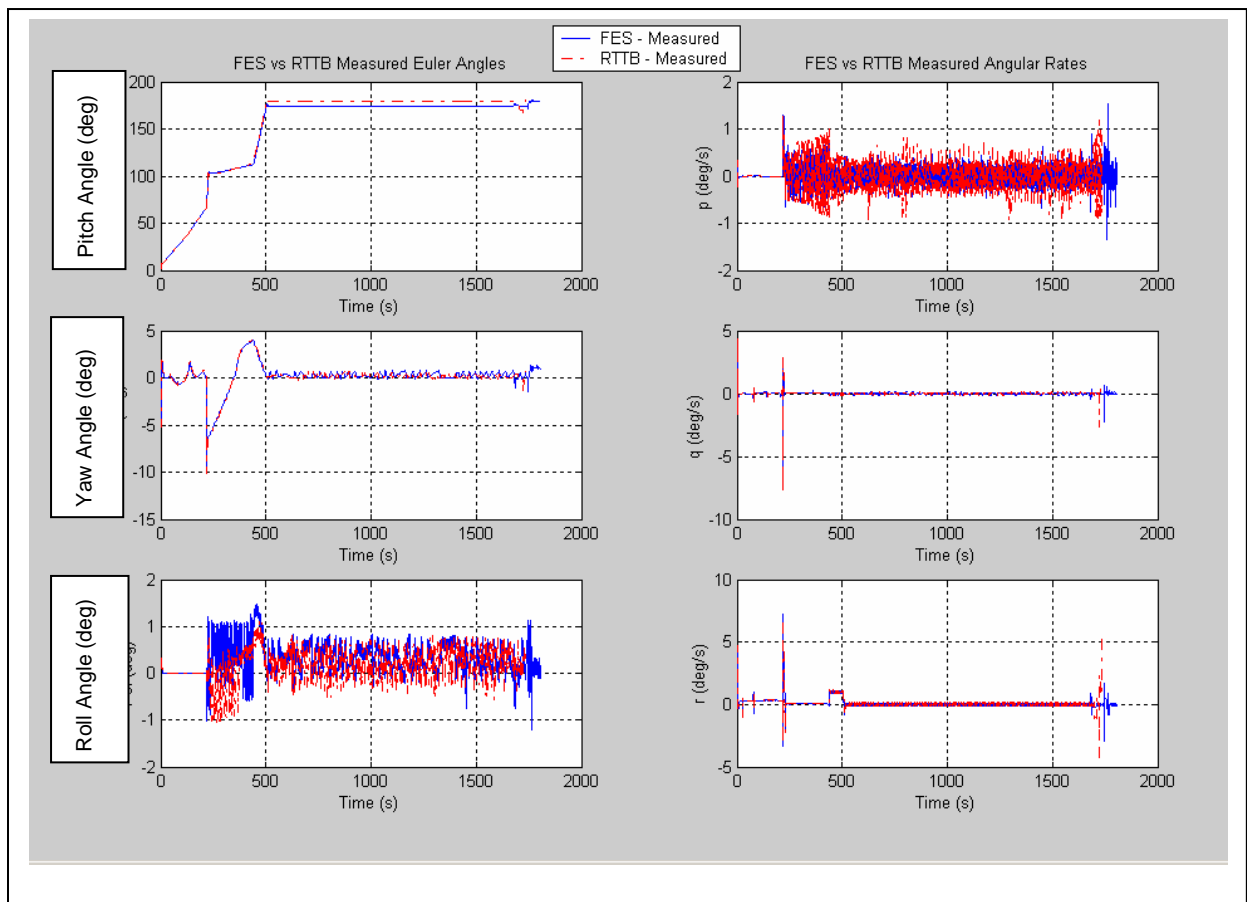


Figure 15 - Test Case 1 Measured Angles & Rates compared between FES and RTTB

8. CONCLUSION

A complete overview of MAV ascent scenarios is addressed for both sample return and manned missions, and the main drivers for the MAV design are highlighted. Spacecraft architecture designs are derived for both kind of missions, and complete MAV design and layout is described.

Then, GNC trade-off is discussed between different identified concepts, and design criteria enable to choose most suitable GNC baseline, from deep analysis including performance assessment for several algorithms.

Eventually, the overall GNC performance is assessed using both a newly developed generic and expandable 6-dof FES for non real-time simulations, and an adapted RTTB for real-time simulations. This GNC performance loop confirms that all the requirements are fulfilled for the MAV, with the selected design.

No major issue is then identified from GNC point of view, since no innovative theory is required to deal with MAV missions.