The IXV GNC Functional Engineering Simulator

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INTRODUCTION

ESA's Intermediate Experimental Vehicle (IXV) project is the next milestone in the history of European re-entry demonstrators [1]. The project is part of the Future Launchers Preparatory Programme and is now in the C2 phase, when many subsystems are undergoing their final detailed designs. Among them, the Guidance Navigation and Control (GNC) is a key subsystem of the vehicle that must pass through an exhaustive verification process to ensure the success of the mission. This paper describes the IXV GNC Functional Engineering Simulator (IXV-FES), which has become the reference simulator for all re-entry GNC design and validation activities within the programme. It is a clear example of a simulator to support the verification of critical elements of a baseline design that is later upgraded with phase C/D models and data.

The IXV-FES is a true 6-DOF re-entry simulator and is specifically designed to support the design, performance assessment and validation of the GNC subsystem (see context diagram in Figure 1), which must control the trajectory of the IXV vehicle during the exoatmospheric phase, from its separation from the launcher to the beginning of the guided trajectory, and during the re-entry phase, from the entry interface point to the opening of the parachute at about 1.4 Mach. The IXV-FES provides the necessary resources to run Monte Carlo simulations and to compute GNC performance index statistics so that the analyst can verify that they comply with the specified GNC requirements.

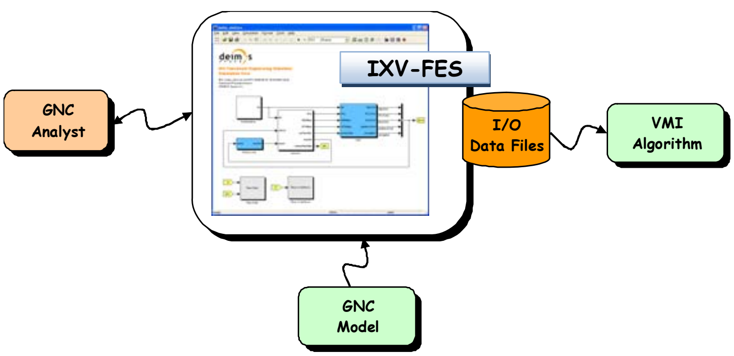

Figure 1: IXV-FES context diagram

BACKGROUND

The ultimate objective of the IXV project is the development and in-flight verification of critical atmospheric re-entry technologies (i.e. aerothermodynamics, hot structures, thermal protection system, GNC, etc.), within the context of the future European space transportation systems. The launch of the IXV mission is due in 2013, on top the new VEGA rocket. The mission features a suborbital flight and a re-entry trajectory with a velocity at the entry gate of about 7.5 km/s, which is fully representative of return missions from low-Earth orbit (LEO).

The IXV vehicle is a lifting body with a Reaction Control System for attitude control during the orbital phase, and two flaps for flight control during the atmospheric re-entry. The entry guidance strategy mainly relies on tracking a drag-energy profile. With regard to the navigation system, it implements a navigation algorithm that merges inertial measurements with GPS updates during orbital and early re-entry phases; and a DDA (Drag Derived Altimeter) update during the blackout phase. On the other hand, the controller structure is based on the separation of the feedforward, feedback and trim contributions.

IXV-FES B2/C1 Activities

The IXV-FES was born to support the GNC design verification activities of the B2/C1 phase, starting in July 2007. The simulator was developed by DEIMOS Space in the frame of the IXV Phase B2/C1 Completion Activities contract, which was awarded to a big industrial consortium where the GNC subsystem was under the responsibility of Astrium Space Transportation, to bring the project from the System Requirement Review (SRR) to the Subsystem Preliminary Design Review (S/SPDR). The simulator was conceived to assess the performances of the GNC subsystem for the IXV reference trajectory with the following features:

- IXV vehicle rigid body dynamics and environment from launcher separation to parachute opening
- Non real-time 3-DOF and 6-DOF simulation
- Monte Carlo simulation with model uncertainties and dispersions

Although the real-time evaluation activities were foreseen for upcoming phases of the IXV project, the simulator design and the vehicle models had to be prepared for easy reuse and real-time implementation, possibly by autocoding, in a future Software Validation Facility (SVF) that had not been defined at the time.

The software was designed, developed and validated by DEIMOS Space, following a development specification provided by Astrium Space Transportation. The simulator specification was a comprehensive document that included a description of the functional architecture of the simulator, the specification of the vehicle models (i.e. environment, dynamics, actuators, sensors, etc.), the definition of the reference frames, generic algorithms (e.g. transformations, quantization, etc.) and also design requirements and coding rules.

The integration of the preliminary GNC algorithm design into the IXV-FES and the actual performance assessment were eventually carried out by the Astrium Space Transportation team.

IXV-FES C2/D Activities

The IXV-FES simulator is now evolving to sustain the activities of the C2 phase of the IXV project, which began in July 2009. The purpose of the C2 phase is to conduct the project towards the next Critical Design Review (CDR) milestone, starting from the preliminary design baseline achieved during the previous B2/C1 stage.

The C2 phase contract was awarded to a new industrial consortium led by Thales Alenia Space as prime contractor. As a result, the C2 activities began with a consolidation phase devoted to review the B2/C1 baseline by updating or endorsing the existing designs and ended in the Consolidation Key Point (CKP) milestone. After successfully passing the CKP, the project underwent the final detailed design phase, which is currently heading towards the Subsystem Critical Design Review (S/SCDR), and will conclude with the System Critical Design Review (SCDR) by the end of 2010.

During the C2 phase, the IXV-FES has been continuously evolving, keeping the vehicle models up to date, as the various vehicle subsystem designs, including the GNC, were being updated and optimised through the design loops. On the other hand, the detailed design of the GNC has revealed the need to update the simulator with higher fidelity environmental models, taking into account more realistic effects that have been identified as relevant for an accurate GNC performance evaluation with respect to the requirements of the mission.

It should be remarked that in the frame of C2 activities, Thales Alenia Space has contributed to the IXV-FES update with the provision of new models, such as ATDB tool, RCS blow-down model and BFC (flap) model. Also, SENER has provided a new high-fidelity thruster model.

THE IXV-FES AND THE IXV PROJECT LIFE CYCLE

The IXV-FES simulator is designed to support the engineering activities through the B and C phases of the IXV project life cycle [2]. This includes support to design, verification & validation, and performance evaluation. The IXV-FES simulations have been used throughout the project life cycle in different ways, depending on the active phase:

- *B2/C1 Phase*: the first fully functional release of the FES (V2.1) was used to validate the performance of the GNC preliminary design at S/SPDR.
- *C2/D Phase*: the FES was used during the consolidation phase in support of the design and evaluation of the new GNC baseline at the CKP. Currently, the FES supports the detailed design of the GNC subsystem while it is upgraded for the validation of the GNC performance at the S/SCDR. At the end of phase C2, the FES will evolve to generate, by autocoding, the dynamic and environmental models for the Real-Time Test Bench where the real-time performance of the GNC will be validated. The outcome of this phase will later provide valuable inputs for the SW and HW specification of the on-board software testing facility.

FES ARCHITECTURE

When the IXV-FES development activity started at the beginning of 2008, the S/SPDR milestone was targeted in November of the same year, which involved that the simulator had to be delivered by July, in 6 months time. Later on, the whole project suffered certain delays but, anyway the schedule of the activity was extremely tight for such a complex simulator.

At this point, the selection of a reuse-oriented software architecture played a critical role to comply with the programmatic constraints of the IXV project in a cost-effective way. The SIMPLAT architecture was eventually selected for the simulator (Figure 2), which allowed a fast sequence of product deliveries:

- First IXV-FES prototype was delivered in April
- Version 1.0 ready for GNC integration was delivered in May
- Version 2.0 with Monte Carlo analysis was delivered in October
- Final validated version 2.1 was accepted in December

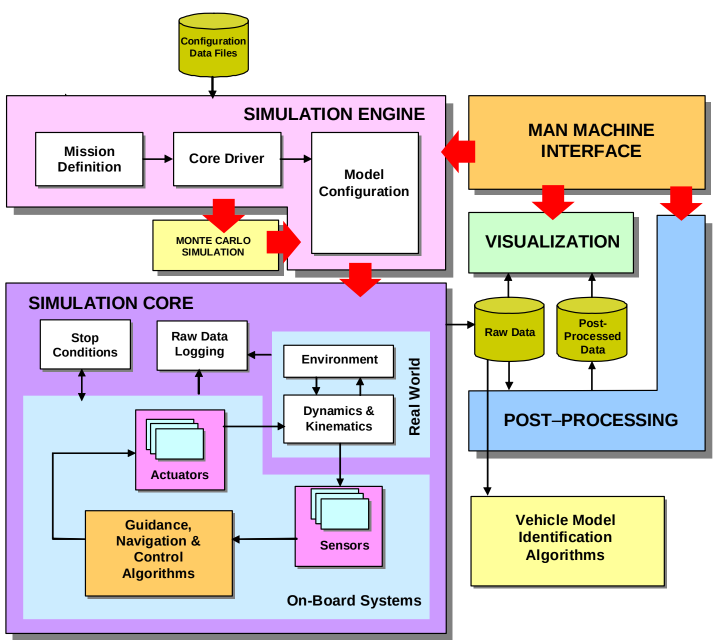

Figure 2: IXV-FES software architecture

SIMPLAT is a simulation infrastructure designed and developed by DEIMOS Space for the production of functional engineering simulators. The SIMPLAT infrastructure is based on the MATLAB™/Simulink™ modelling & simulation environment and provides all the basic functionalities needed by a FES tool, so that project-specific elements can be rapidly built on top of it. SIMPLAT operation largely relies on its XML database, which stores model, scenario and simulation parameters. SIMPLAT includes Monte Carlo simulation and analysis capabilities and several generic toolboxes and blocksets.

The main components of the FES architecture are the following ones:

- *Simulation Engine*: responsible for the complete definition of a simulation scenario, including the definition of the mission and the configuration of the models to be simulated. It loads the parameters of the mission from the Configuration Data Files (XML files). The parameters of the mission are pre-processed to obtain model and simulation parameters, and the models are configured accordingly by setting their mask parameters. This component also controls the execution of the simulation.
- *Simulation Core*: it represents where the numerical integration of the system dynamics is carried-out. In general, it consists of a Simulink template, which is customized for each operation mode by replacing the applicable models taken from various Simulink libraries.
- *Monte Carlo Simulation*: comprises a number of functions that manage the configuration and control of Monte Carlo simulations. It generates perturbed values of the model parameters (applying dispersions and uncertainties) and controls the storage of the raw data so that they can be further processed.
- *MMI*: provides user interface functions that give access to the principal functionalities of the simulator, namely simulation, post-processing and visualization. In the case of the GNC FES, the implementation of the MMI is a menu-based GUI.
- *Visualization*: its purpose is to generate graphical representations or plots of the simulation raw data and of the post-processed data (system budgets and Figures of Merit). The graphical outputs are integrated into the MMI for user convenience.
- *Post-Processing*: it provides functions for processing the raw data obtained in the simulations. They compute system budgets and performance indexes.

FES FEATURES AND DESIGN

The IXV-FES software design has been inspired by the objectives of the project and the intended use of the simulator, always within a context of maximum cost-effectiveness and adherence to the project schedule:

- Representative numerical simulation environment of the IXV mission
- Validation and performance assessment of GNC algorithms
- Validation and assessment of VMI (Vehicle Model Identification) algorithms
- Autocoding-ready modelling for future real-time assessments in C/D phase

The FES can simulate the following scenarios in terms of IXV mission phases:

- The exoatmospheric phase: from the vehicle separation from the launcher to the start of the guided trajectory
- The re-entry phase: from the Entry Interface Point at 120 km altitude, to the opening of the parachute
- The two controlled phases (exoatmospheric + re-entry) together: this case covers the whole period during which the GNC is activated

The simulator supports two types of simulations as for the dynamic models used:

- 3-DOF simulation: in this case, only the translational dynamics is simulated, considering the external forces acting on the vehicle, but not the external moments. The attitude of the vehicle is not simulated but derived by geometrical relationships from the angles commanded by the guidance algorithm, which is equivalent to suppose that the control is ideal. This simulation is mainly intended for guidance testing.

- 6-DOF simulation: in this case both translational and rotational dynamics are propagated taking into account external forces and moments. The equations of motion correspond to a formulation of orbital mechanics (i.e. expressed in inertial axes), which is more convenient to cover the orbital phase than the usual wind axes formulation of the re-entry simulators. This simulation is intended for evaluation of the complete GNC.

In fact, these two options allow the GNC designer to carry out 3-DOF analyses (assuming ideal control or ideal navigation) and 6-DOF analyses (with real control and navigation).

The FES includes the following environment and vehicle Simulink™ models (see model library in Figure 3):

- Atmosphere model: the first release of the simulator included the CIRA-88 model and a tabular model based on the USSA-1976.
- Wind model: the user can select two models. The tabulated wind model is a horizontal wind model based on a look-up table where wind speed components are interpolated as a function of the altitude. The turbulent wind model implements a spectral representation of continuous wind turbulence similar to the Dryden model.
- Gravity model: takes into account the J2 zonal harmonic term.
- Equations of motion: 3-DOF and 6-DOF dynamics.
- Force and moment perturbations: this model allows the injection of force and moment perturbation profiles as a function of the flight time, representing perturbations due to unmodelled effects.
- IXV aerodynamic database: the first release of the FES included the IXV aerodynamic database version 2.2 covering the hypersonic and transonic regimes.
- Mass centering and inertia (MCI): the total mass of the vehicle varies as the RCS propellant is consumed. The position of the centre of gravity and the inertia matrix are interpolated in a look-up table as a function of the total mass.
- Reaction Control System (RCS): this actuator model receives on/off commands and considers various non-ideal effects like fuel consumption, minimum impulse bit, response delay, maximum thrust depending on the static pressure of the propellant tank, plume effects modelled as output moment uncertainty.
- Flaps: the flap actuator model takes into account saturations, maximum deflection rates, bias, dead zone, response dynamics.
- Inertial Measurement Unit (IMU): the IMU sensor model produces velocity increments and attitude measurements, taking into account misalignment, scale factor error, bias, noise, delay and quantization.
- Global Positioning System (GPS): the GPS model is a performance model based on adding bias, noise and quantization effects to the ideal measurements.

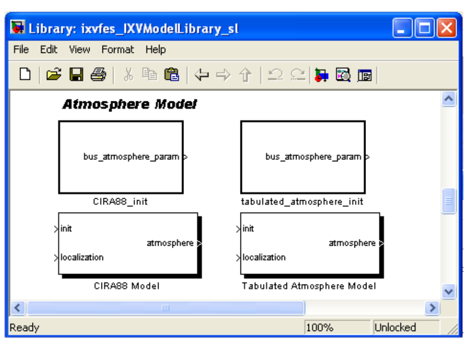

Figure 3: IXV Model Library showing atmosphere models

A Simulink modelling requirement included in the FES development specification was that the initialisation and treatment parts of the models had to be separated (as can be seen in Figure 4). This requirement was intended to facilitate the autocoding of the models for real-time assessment in upcoming phases of the project. Consequently, all the models were provided with initialisation blocks that define the model parameters and constants, which are wired through signal buses to the treatment parts of the models.

Some additional simulation capabilities of the IXV-FES are:

- The user can select single run or Monte Carlo simulations. In the Monte Carlo configuration, it is possible to select a subset of the total number of draws for simulation.
- The simulator can reproduce a single draw from some already run Monte Carlo simulation. This feature is very useful for the analysis of worst cases.
- The FES can run simulations in rapid simulation mode, using Real-Time Workshop to autocode the Simulink model to a Rapid Simulation target, which actually consists of a stand-alone executable. This feature significantly shortens the required CPU time, which is extremely useful in 6-DOF Monte Carlo simulations.

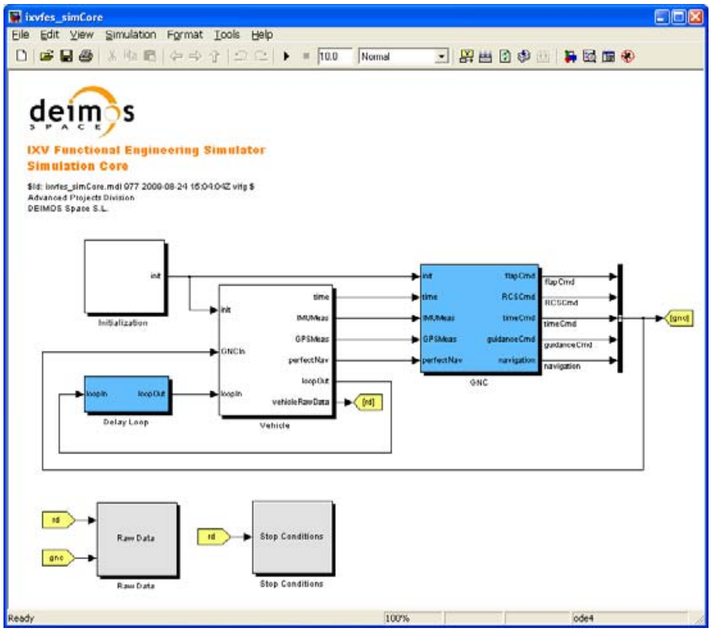

Figure 4: IXV-FES Simulation Core showing initialisation and treatment blocks

Other analysis capabilities of the FES are:

- Automatic generation of simulation output plots defined in the XML database.
- User defined plots and post-processing functions.
- Automatic computation of figures of merit (FOM): maximum, time of occurrence, condition, duration. The simulator can generate FOM reports.
- Monte Carlo statistical analysis: maximum, minimum, mean, standard deviation.

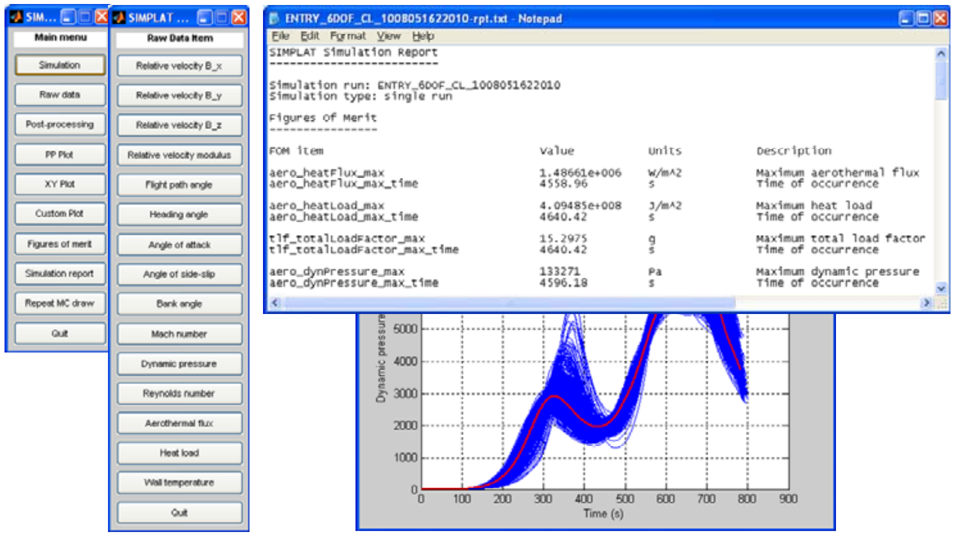

Figure 5: IXV-FES MMI and results

FES UPGRADE FOR CDR

During the consolidation phase that ended with the CKP milestone, various FES upgrade needs were indentified. Most of them refer to the vehicle and environment models and consist of modelling new effects, either by model update or replacement, so that the GNC performance validation can achieve higher reliability in agreement with the requirements of a detailed design phase.

The most relevant FES upgrades done during the C2 phase were:

- New tabulated atmosphere model has been added with data from statistical analysis of the NRLMSISE-00 model. Atmospheric temperature uncertainty has been added. The existing USSA-1976 tabulated atmosphere model is now considered in orbital phase simulations.
- New tabulated wind model has been added with data from statistical analysis of the HWM-93 model, including uncertainty.
- The IXV aerodynamic database has been updated to version 3.1.3b.
- The MCI model has been updated with TPS (Thermal Protection System) mass consumption data
- The RCS model has been updated with a new high-fidelity thruster model, and new maximum thrust and fuel rate look-up tables.
- The flaps model has been updated to include the backlash effect. The capability to compute hinge moments has been added as a new post-processing function.
- The parameters of the IMU model have been updated with data corresponding to the QUASAR 3000 inertia reference system. Moreover, the quantization effect was added to the quaternion measurements and random walk noise was also modelled.

FES VALIDATION

The IXV-FES simulator was validated according to a thorough Software Verification and Validation Plan, as can be expected for a B/C phase FES. The plan complies with the ECSS-E-40 standard and comprises the following test designs:

- Model Test Design: unit testing of all the vehicle and environment models with the exception of the aerodynamic database model, which was already validated.

- FES Unit Test Design: unit testing of the project-specific toolboxes of MATLAB functions (e.g. the rigid body kinematics toolbox).
- FES Functional Test Design: functional validation of the simulator with respect to the IXV reference trajectory in open-loop, testing the capability of the FES to reproduce it.
- FES Integration Test Design: validation of the correct integration of GNC-relevant IXV models (e.g. RCS, flaps) into the FES.
- FES System Test Design: system tests for validation with respect to the Technical Specification.
- FES Regression Test Design: selection of tests to be re-run for the detection of regression errors.

MONTE CARLO SIMULATION

The Monte Carlo simulation is the fundamental method for the validation of the GNC in off-nominal conditions. This operation mode is adequately supported by the IXV-FES. The dispersions and uncertainties that have been configured in the simulator for running Monte Carlo simulations are the following ones:

- Initial state (i.e. position, velocity, attitude and angular velocity)
- Atmospheric density and temperature
- Thruster force, moments, and nozzle location and orientation
- Mass, centering and inertia
- Flap deflection static offset
- Aerodynamic database uncertainties

The simulator has the capability to obtain basic statistics from the Monte Carlo simulation results. Anyhow, as all the simulation outputs are saved to file, the users can always write their own code for performing other statistical computations.

From a practical point of view, the execution of a GNC validation plan at the level of detail required during B/C phase activities is highly troublesome. In this respect, the IXV-FES simulation implements specific solutions to cope with them.

Re-entry GNC simulation is highly demanding in terms of computational resources and hardware infrastructures. The simulator includes high fidelity environmental models, full 6-DOF vehicle dynamics and complex guidance, navigation and control algorithms, which impose a substantial computational load to the system. In terms of data storage needs, Monte Carlo simulations often comprise 1000 repetitions, using a short simulation step of a few milliseconds along more than 1000 seconds and can generate up to 100 Gbytes of data for post-simulation analysis.

The IXV-FES provides the following functionalities specifically devised for handling Monte Carlo simulations:

- Rapid simulation mode: in this mode the Simulation Core (i.e. the Simulink model) is autocoded to a single stand-alone executable. This way the duration of Monte Carlo simulations can be shorten by a factor 5 to 10 depending on the model.
- Optimal selection of simulation and post-processing outputs: the XML database can be configured so that only the outputs needed for GNC performance evaluation are actually saved to file. This saves simulation time and data storage space.
- Output downsampling: the simulator includes a function for downsampling the simulation and post-processing outputs saved to file for plotting purposes. By reducing the size of simulation output files, the generation of plots and the transfer of simulation folders gets faster.

CONCLUSIONS

The IXV GNC Functional Engineering Simulator has been supporting the GNC engineering activities of the B/C phases of the IXV project, from the preliminary design to the detailed design, now ongoing. The simulator was developed within a context of tight programmatic constraints taking advantage of the reusable SIMPLAT simulation infrastructure. The IXV-FES has proved being flexible enough to evolve according to the progress of the project, along the critical design phases of the work plan. In fact, the IXV-FES has been reused in other entry-related ESA activities, with minimum additional effort. For example, in the frame of the contract entitled “Robust Skip Entry Guidance and Control Techniques”, the simulator has been extended with a model of the ARD vehicle and with functions for computing specific guidance performance indices, and is being utilized to assess and validate new skip-entry guidance algorithms.

It has been shown that the IXV-FES simulator is entirely adequate for the performance assessment and validation of the GNC subsystem of the IXV vehicle in nominal and off-nominal conditions and is even prepared to generate by autocoding models that could be executed inside a future Real-Time Test Bench.

ACKNOWLEDGEMENTS

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