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# A flexible real-time simulation platform dedicated to embedded rocket engine control systems development and testing

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## Abstract

Electrical actuators are progressively replacing historical pneumatic systems to control rocket engine valves. This technology not only supresses helium consumption and reduces costs but also greatly facilitates in-flight rocket engine regulation and throttling.

Regulation & throttling algorithms can strongly depend on the application, from simple regulation to improve launcher performance, to deep throttling for landing, or soft start-up and shut-down for reusable engines. The range of actuator technologies and power levels is also wide. Testing a newly developed controller directly on an engine fire test can be risky, especially for new engines. Moreover the capability to test the embedded hardware in a wide range of demanding conditions will probably be limited because of costs associated to those tests.

Thus, a flexible real-time test bench that can be adapted to a wide variety of applications can really secure the development and testing of new control chains.

During the past years, CNES and Airbus Safran Launchers have developed and built a platform that can host real actuators and controller hardware, along with real-time models of launcher stage and engine, coupled with a newly designed tool simulating the resisting torque on the actuator.

A first demonstration of a complete hardware-in-the-loop simulation has been achieved in December 2015, validating the capability of the platform to pave the way for Ariane 6 or next generation engines.

## 1. Motivations and general Context

The capability to have an in-flight feedback control loop on thrust and mixture ratio offers performance increase opportunity thanks to optimization of the operating point and reduction of ground biases but also the possibilities to improve the reliability, to reduce the dry mass and offer the capability to have an evolutionary system thank to the software.

Moreover, electrical actuators are progressively replacing historical pneumatic systems to control rocket engine valves. This technology not only suppresses helium consumption and reduces costs but also greatly facilitates in-flight rocket engine regulation and throttling [11].

Future European engines may require throttling, either for performance optimization, acceleration limitation or landing. In-flight control can also relax sub-system conception by a better mastering of their operating domain and by making possible softer start-up and shutdown transients. Cost of subsystems could also be reduced by relaxation of critical fabrication tolerances or, in the case of valves, by suppression of mechanical stop systems.

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Regulation & throttling algorithms will thus soon become embedded systems. Their definition and architecture can strongly depend on the application. The range of actuator technologies and power levels is also wide. Testing a newly developed controller directly on an engine fire test can be risky, especially for new engines. Moreover the capability to test the embedded hardware in a wide range of demanding conditions will probably be limited because of costs associated to those tests. In order to face these challenges, CNES decided to fund a flexible real-time test bench to be developed by Snecma Vernon (former name of Airbus Safran Launchers / Vernon), aiming at a platform which can be adapted to a wide variety of applications and can really secure the development and testing of new control software, hardware and more widely the overall control architecture. This project was named “ISFM” standing for “Installation Simulation Fonctionnelle Moteur” which can be translated as Engine Functional Simulation Platform.

In order to achieve these objectives, a set of technological building blocks have to be developed, among them electromechanical components (valve actuators and electromechanical tools to simulate resisting torque behavior), dedicated control algorithms and calculator capable of embedding them, as well as real-time engine models in order to test them. Along with Airbus Safran Launchers / Vernon, several industrial partners, including small businesses, are involved in the development of the platform, as can be seen on Figure 1.


**Figure 1: Contributors to the flexible real-time rocket engine control systems platform (ISFM)**

The paper will describe in more detail the target configuration of the test bench for its first demonstrations and the technological building blocks that have been or are being developed for this purpose. A first demonstration of a complete hardware-in-the-loop simulation has been achieved in December 2015, validating the capability of the platform to pave the way for next generation engines. The use case retained for the qualification of the test bench is the Vinci Engine. The paper will then highlight the future works foreseen on this new test bench.

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# 2. Plateform general presentation

## 2.1 Goal of the test bench

The principle of a Hardware-In-The-Loop simulation platform is to put together software components and real equipment. The software components are integrated on a real time computer. The main goal is to demonstrate architecture concepts, develop and tune control loops at early phases of the project.

The software components are the various models that participate to the simulation of the system (generally called “plant”). In our use case, the propulsive stage simulation including the propellant consumption and the real time engine models are the main components necessary for the engine control loop shaping and validation. The control software can be integrated on this platform or on a dedicated controller depending on the degree of maturity of the tests. At the beginning of the project, equipment is not available. Most of equipment has been simulated. They are gradually replaced by real equipment during the integration process of the platform.

Two categories of hardware components are used on the test bench.

On one hand, there are the components under tests which are serial or prototype equipment likely to be integrated on the final engine. This equipment is part of the command and acquisition chains (actuators, sensors, controllers, electrical generators). Actually, this equipment should be as representative as possible to catch the physical limits of the system and to challenge the control software. It is also necessary to get a high level of fidelity to generate realistic failure cases to test the FDIR (Fault Detection Isolation & Recovery) logics that are fundamental strategies for space systems generally based on duplex architectures with complex reconfiguration rules.

On the other hand, tooling equipment is used to serve the simulation by generating the appropriate stimulations on the equipment under tests. To this category belong the tools that apply a counter torque on the actuators, the power sources that energize the controllers, the cards that emulate sensors to feed equipment with representative electrical signals and the communication system with the adequate protocol (Ethernet, CAN, etc.)

This flexible hardware-in-the-loop test bench allows to be adapted to the overall propulsive system either for the first stage (engine cluster or alone) or for an upper stage.

This test bench is also suitable to perform qualification tests with final hardware and software components and is likely to take part to the production process during the equipment pass-off tests before integration on the engine. The flexible scalability of the platform is based on:

- a modular design allowed by open-source components,
- an integration process of the software components based on automatic code generation with widely spread standard software,
- over-sized performances of the real-time OS,
- numerous and modular electrical interfaces that can be completed with additional card to extend the capacity.

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## 2.2 ISFM Plateform - a modular architecture

The functional architecture is described in Figure 2. Industrial external bays with a high level of compatibility based on a non-proprietary interface protocols have been retained. Some communications buses protocols are natively available - Ethernet, CAN BUS - but a wide range of cards are likely to be connected to the bay to extend its capacity and reproduce the launchers buses operation.

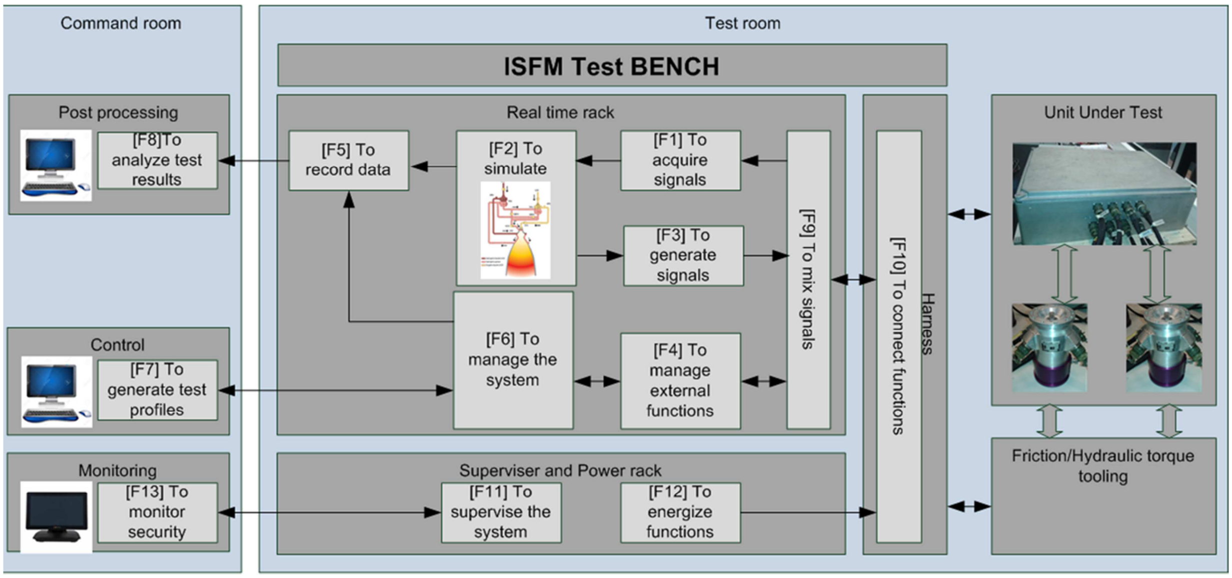


**Figure 2: functional architecture of the real time test bench**

## 2.3 Models integration process

One of the main requirements of the platform is its compatibility with models of various origins.

Simulink models are generally used during prototyping phase to simulate the controller and simplified physical models. Simulink models are compatible with many real time platform, Concurrent, National instrument, dSPACE.

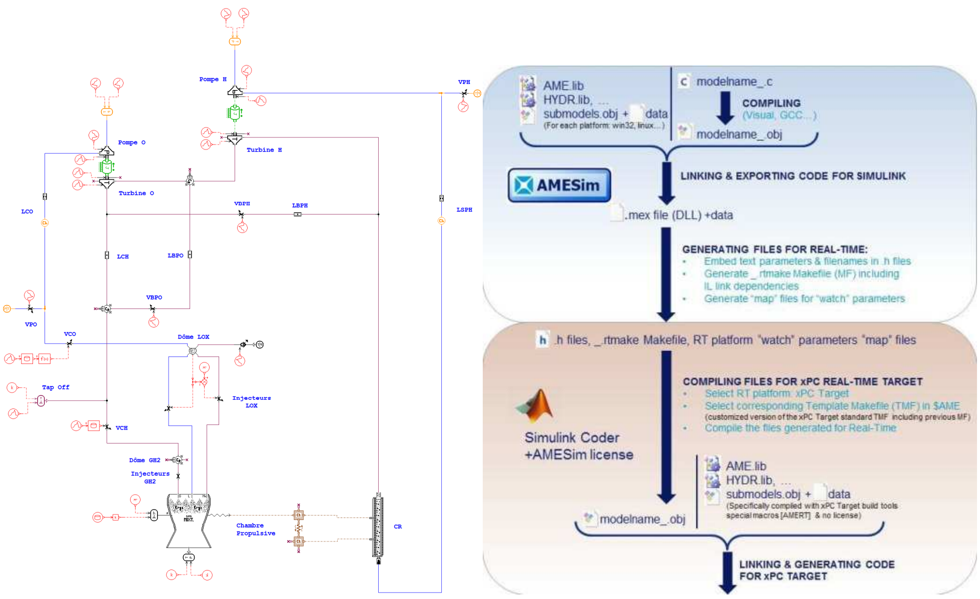


**Figure 3: Engine model and its integration process of the test bench - this process ensures the efficiency of this key phase**

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But physical models are more commonly developed on AMESim software or directly in languages like fortran or C-code (such as Matlab S-function for example).
The need to get the best possible real time transient model of the engine oriented the development toward a model reduction analysis of our full transient model by cutting-off the high frequency phenomenon, simplifying physics, etc.
The reduced model made compatible with real time constraints was then integrated as described on Figure 3.
The integration process is user friendly and avoids any disruption of the configuration management of the models.

## 3. Description of the platform components

### 3.1 Propellant active management algorithm

Propellant active management (P.A.M.) is a way to increase launcher performance due to reduction of propellant performance reserves and knowledge of the real loaded propellant mass. Several ways of implementing propellant management are currently under study in France. P.A.M. can be directly linked with control valves, as proposed in [2] or combined with a closed-loop at engine level to improve performance even more. In the frame of the ISFM project, ASL/Vernon developed a P.A.M. algorithm based on various measurements including punctual level probes, tank pressure and temperature, acceleration and attitude. Software includes detailed modelling of the tanks and numerous functionalities

Software was coded so as to be easily adapted to various tank geometry, level probes number and positioning and contributors to uncertainties on remaining mass estimation.

One of the specificities of the P.A.M. software proposed in the frame of ISFM is its interaction with the engine control application software (ECAS): indeed, the former includes a mixture ratio estimator. Different strategies of P.A.M can be evaluated either with discret or continuous probes and with particular form of the tank. Thank this computation means, it is possible to demonstrate the real gain in accordance with the probe location inside the tank. For example, at every passing of a level probe, engine mixture ratio estimator is corrected and between two level probes, engine mixture ratio estimator can be used to calculate the remaining masses and adapt the mixture ratio command.

### 3.2 Engine Control Application Software - ECAS

The engine control application software (ECAS) is the core of the “big loop” (closed loop on engine chamber pressure and mixture ratio). ECAS does not only include the control law but all the functionalities that are necessary for an embedded regulation such as:

- consolidation and treatment of engine measurements, including a mixture ratio estimator based on a small neural network (assumption of no flow meters in flight)
- adaptation (filtering or saturation) of chamber pressure and mixture ratio command coming from P.A.M. or launcher on-board computer in order to protect the engine and the control loop from functional or mechanical limitations crossing,
- anti-windup, dead band
- operating modes (open-loop closed-loop) management and status indicator.

General scheme of ECAS is presented in the Figure 4.

For the first complete hardware in the loop tests of the ISFM platform, ECAS does not include start-up and shutdown sequence management and is located on the real time computer bay. However, for other projects like the subscale cryogenic engine demonstrator BOREAS [3], ECAS will be embedded on a calculator/REEC hardware and include full engine sequence management (from chill-down to shutdown transient).

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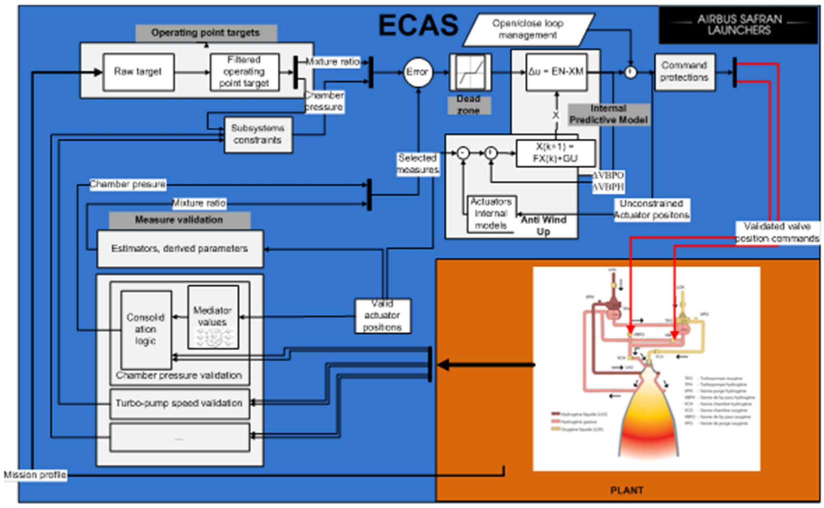
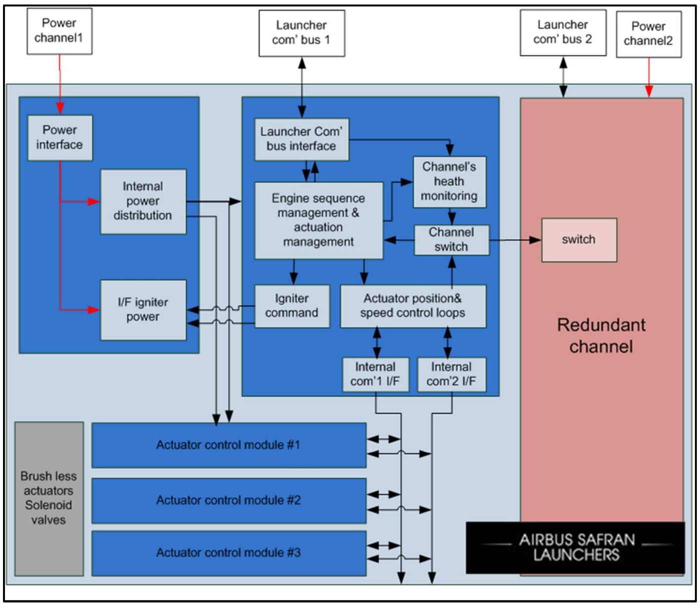



**Figure 4: Engine Control Algorithm Software architecture**

### 3.3 Rocket Engine Electronic Controller Demonstrator- REEC Demo




The Rocket Engine Controller Demonstrator is a fault tolerant controller based on two redundant and segregated channels. Each channel is connected to one power bus and one Ethernet communication bus. The REEC Demo controls one of the two motors of the actuator (cold redundancy).

It is equipped with a health monitoring function that disconnects the active channel and enable the redundant channel upon detection of a fault.
Demonstrator hardware is based on dSPACE bread boards for software integration (position, health monitoring, mode management, etc.) and specific power cards for speed and Current/Torque control loop

**Figure 5: Engine Controller functional architecture**

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### 3.4 Actuators

The actuators tested are electrical. In a real engine, valves are composed by 3 parts: the hydraulic part, the actuator part and the electronics command part. This electronic command converts the electrical power into electrical currents in the brushless motor phases in accordance with the valve specification in term of manoeuvring time and accuracy.

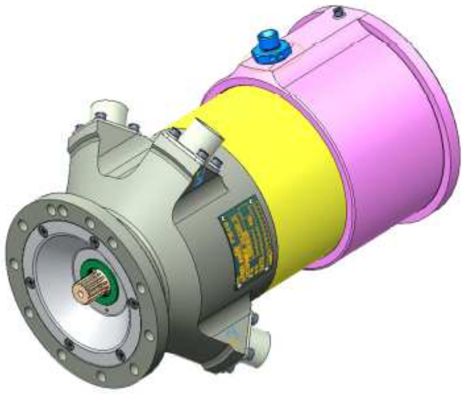

**Figure 6: Valve actuator**

For the ISFM platform, the hydraulic part is suppressed and replaced by another actuator which provides a resistive torque in accordance with what is computed by the real time software (see 3.5).

The actuator is composed of two redundant brushless electrical motors with shafts linked through a reduction gear. Even if these actuators will not be used at engine fire test, it uses technologies that are able to sustain a real engine condition. For this reason, the acceptance tests are not only tested in ambient condition but also with vibration and cold condition. This is the only part of the demonstration that can be used as it is in further development.

### 3.5 Torque generation tool

The load tool is composed of four torque generators aiming at reproducing the resistive torques produces by a rocket engine fluid valve (dry friction and hydrodynamic torques).
A control bay allows interfacing torque generation tool with the real time simulation: the torque generation tool receives dry friction and hydrodynamic torque command and sends back its real time angular position and realised torque via analogical signal.

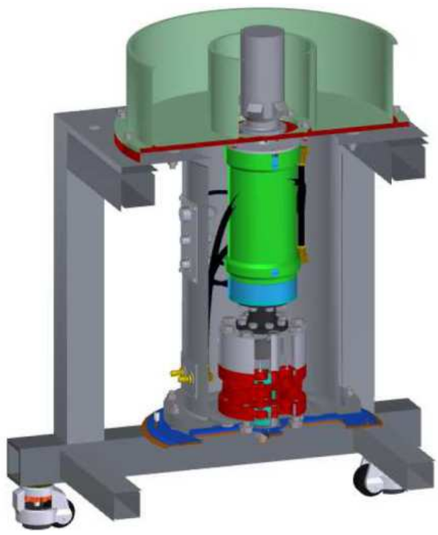

**Figure 7: torque generation tool**

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### 3.6 Engine Real-Time model

Engine transient models used for the engine development are generally not compatible with real-time computation since they are heavy and complex calculations. Thus, activities were lead in order to build a real time transient model which can describe the Vinci (first application chosen to demonstration) engine dynamic behaviour for the ISFM platform. Before the beginning of this activity, the simulation duration of a start-up or shut-down transient (duration roughly 5s) on a personal computer was one hour.

A simplified model was developed to be compatible with the real time approach.

The number of variable to describe the physics (initially several hundreds) was divided by one order of magnitude. Thanks to this simplification, a start-up or shut-down transient can be simulated in 1,5s. It means that for a loop duration objective of 1ms, in the model developed the loop duration is about 200µs.

This model is compared to real engine tests data with successful results and implemented for software in the loop and hardware in the loop tests on the platform.

## 4. Validation logic and first results

The validation logic is based on two main steps.

- First, the validation of the separate components of the control loop is performed:
  - o Validation of each software components on PC with Matlab/Simulink ®. This includes both unit tests and functional tests performed at this stage with a model of the plant including the space engine model.
  - o Environmental qualification of the actuators with representative conditions ( pressure , temperature, vibrations, counter- torque ...)
  - o Validation of the controller coupled to the actuators
- Then, the software components are integrated on the real time test bench taking advantage of an automatic code generation using the Matlab software suite linked with the Simulation Work bench® tool kit provided by Concurrent. Functional tests in a pure software environment are performed on the RT test bench and compared with those got during the prototype design with Matlab to ensure the correct implementation of the code on the ISFM test bench. At the end, stubs previously used to simulate the actuators are replaced by the real equipment: controller and actuators

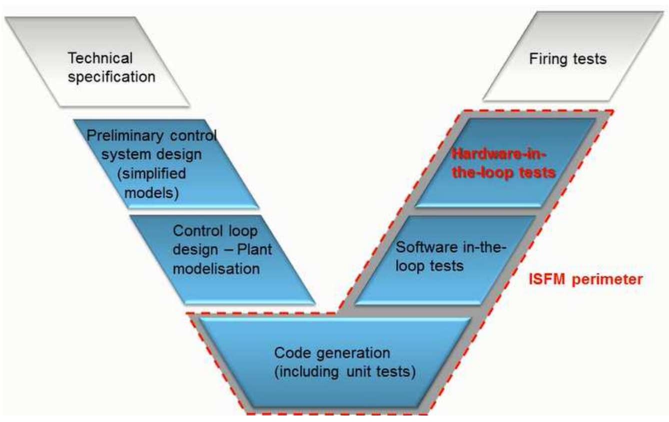


**Figure 8: V-cycle- versus ISFM perimeter**

The qualification tests are performed at system level in accordance with the qualification plan. The control software is tuned to fit the real performances of the equipment. Performances of the whole system are characterized:

- in nominal configuration (Figure 9)
- when facing scattered conditions of the plant, for instance by modifying efficiency of the sub-systems (pressure losses of injectors, etc.)
- under modelling of sensor noise or functional failure mode
- when facing failure cases at both software level and equipment level triggering short circuits on the H-bridge of the controller, voltage loss, actuator's angular acquisition disruption and so –on. These failure cases are deduced from the RAMS analyses performed during the design phase.

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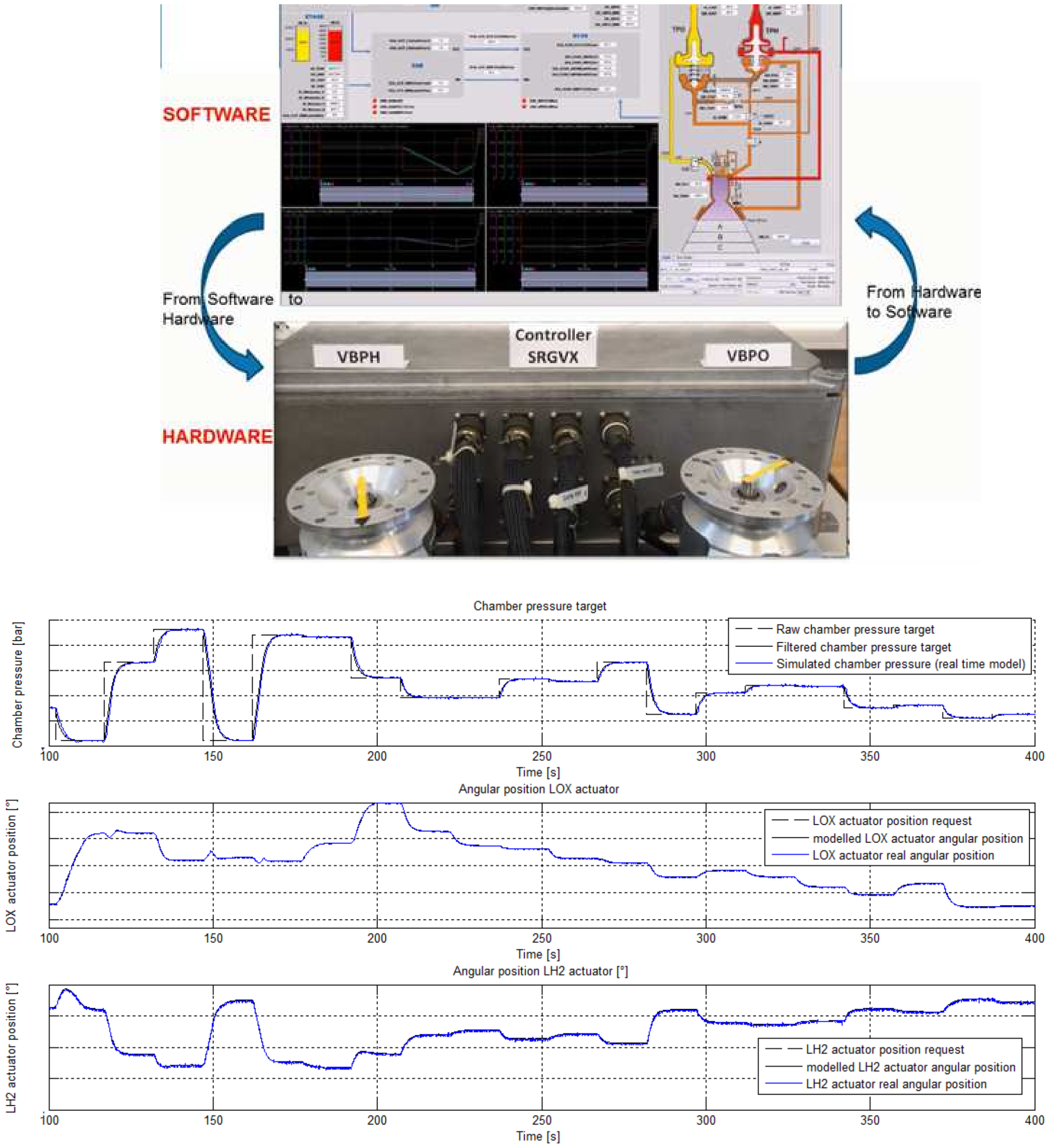


**Figure 9: The ability of the control software to correctly control the thrust with adequate commands is verified in the whole flight domain with relevant interface conditions and mechanical torque**

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## 5. Future work and perspective

The ISFM test bench will be operational from end of this year and will contribute to the validation of future engine electrical command laws. A modular approach is adopted for welcoming new costumers. Each customer has to provide real-time model of the engine and specific hardware. ISFM will be the platform for:

- BOREAS, a 10kN Lox-LH2 expander bleed demonstrator, in the frame of CNES-ASL Co-funded demonstration Project. It will be the first application. It is a “small size” system technological platform allowing integrating disruptive technologies. It has a throttling capability from 5 up to 12kN + idle modes. Concerning electronics, the sequence management and the ECAS code are in the COTS calculator
  The real-time model of the engine is on development followed by ISFM SWIL tests. The ISFM HWIL test campaign is planned 2$^{nd}$ semester 2017 in order to prepare the DLR P8.3 engine firing tests in 2019, with the final objective to use the calculator to regulate the engine.

- PROMETHEUS demonstrator is the Ultra-Low-Cost reusable methane engine 100 tons of thrust in the frame of ESA/FLPP program aiming at strongly reducing the cost of cryogenic propulsion through technological efforts including new process such as the Additive Layer Manufacturing. This engine will allow multiple re-ignition and deep thrust modulation (30-110%).
  Once the design of the Prometheus controller, the definition of HMS algorithms and a real-time model of the engine will be available next year, ISFM SWIL tests will be carried out. Afterwards, in 2019 ISFM HWIL test campaign will be performed with the specific hardware (REEC, electrical actuators) developed for the demonstrator. The Prometheus REEC/HMS will be used for the engine firing test at DLR P5 bench at Lampoldshausen in 2021.

Depending on future test results possible R&D activities are close loop control of start-up & shutdown, new mixture ratio estimators. More far away, the system is adapted to demonstrate the Health Control Interaction concept [9][12] such as AFTC “Automatic Fault Tolerant Control” [5][6][8][10] or IVHM propulsion modules in integrating the Real Time Health Monitoring System [7].

## 6. Conclusion

The maturation of technologies has always been an important objective for CNES [4]. The effort must be pursued allowing French and European Industry to be competitive. Thus major concern for the preparation of future launch systems is cost reduction. The engine electrification (electrification of actuators) and the optimization of the control system lead to the elimination of Helium Control Systems but not only. It allows in-flight rocket engine regulation and throttling.

ISFM project started in 2011 under a government Investment Plan « PIA » and was followed by CNES-ASL co-funded demonstrator project. ISFM SWIL test campaign was successful by the end of last year. Dedicated hardware, REEC and brushless actuators, have been delivered and acceptance test have been successful as well. Final ISFM HWIL validation tests, for Vinci engine application, are ongoing and will be achieved by the end of this year.

The real time test bench ISFM, becomes for ASL a basic platform for the development of the engine control laws and regulation. It is strongly modular, allowing to mature necessary technologies (TRL) covering from software up to hardware-in-the-loop.

The ISFM test bench will be operational from end of this year and will contribute to the validation of future engine electrical command laws. First application will be BOREAS demonstrator, the second one will be PROMETHEUS demonstrator aiming at preparing the use of the regulating / HMS system during the engine firing tests.

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