Testing AOCS or ESP – Are There Real Differences?

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INTRODUCTION

If one compares Attitude and Orbit Control Systems (AOCS) for satellites and Electronic Stability Systems (ESP) for vehicles superficially, there are not many similarities except that they are both electronic devices for positioning control. But the technical structures, the development processes and especially the testing processes of these electronic units have many similarities which are important from the point of view of the test system. In both areas, automotive and space, hardware-in-the-loop (HIL) testing is a widely used test and development method. As a market leader, dSPACE has developed a tool chain that is highly suited for HIL testing in automotive applications. The tool chain includes hardware and software components and focuses especially on test requirements in the automotive field. It is used worldwide in hundreds of installations and has virtually become standard equipment in the development processes of many car manufacturers and component suppliers. This paper describes the use of the HIL tool chain in space applications and shows that many of the requirements for test systems in automotive electronics can also be found in space test systems. This makes it possible to directly transfer the solutions from one field to the other. Nevertheless, there are differences in the development and test processes, and these give rise to different requirements. These differences are described here, and solutions for a space HIL test system are presented.

Comparison of HIL Test Philosophies in Automotive and Space Applications

Basically, both AOCS, an example of a controller system in space applications, and ESP, a representative of automotive electronics, are electronic control units (ECUs) with electrical inputs/outputs and bus connections for sensor and actuator connections and for communication. Thus, the general structure of HIL test systems is the same for both of them. The HIL simulators have to have electrical outputs for sensor signal generation, inputs for actuator signal measurement and a real-time processing unit for plant model calculation. On the software side, real-time capable models and some test and experiment software for simulator control are necessary. The differences in test systems become apparent on taking a closer look at these components. They arise from the different philosophies and test use cases in the development processes for automotive and space electronics.

Automotive HIL systems are mostly used for testing and validating the ECU software functionality on the target hardware. A final evaluation of the complete system is always performed with in-vehicle tests in prototypes. Series ECUs for vehicle production are not tested at all. The goal of an automotive HIL simulator is to test as much software functionality as possible automatically. The main factors in this are:

- The highly sophisticated diagnostic capabilities of an ECU
- The huge number of software variants on the same ECU hardware due to different vehicle configurations
- The different software versions in the development process
- The strong interaction between different ECUs in the ECU network of a vehicle.

Space applications have a different development philosophy. HIL systems are used as special check-out equipment during the development process. Satellite engineering models and flight models are tested intensively as whole systems up until final launch. In the ECU environment, real systems like sensors and actuators, communication partners and also mechanical systems have to be taken into account just as much, because a later real-world test before the launch is (of course) not possible.

HIL TEST SYSTEMS IN THE DEVELOPMENT PROCESS OF AUTOMOTIVE ELECTRONICS

Automotive HIL systems range from small component test systems with the focus on testing a single ECU to so-called virtual vehicle HIL systems (VV-HIL) where the entire ECU network of a vehicle is connected to the simulator. A VV-HIL consists of several cabinets with their own processor power, I/O channels and bus communication, Fig. 1. The ECUs are often integrated directly inside the simulator cabinets.

Fig. 1: Virtual vehicle HIL system for testing a mid-range vehicle ([1])

As the software validation of an ECU is the focus of an automotive HIL system, in most cases just the electronic device under test (DUT) itself is connected. The HIL system simulates as many surrounding components as possible. The general structure of a component test system is shown in Fig. 2. The components are described according to [2].

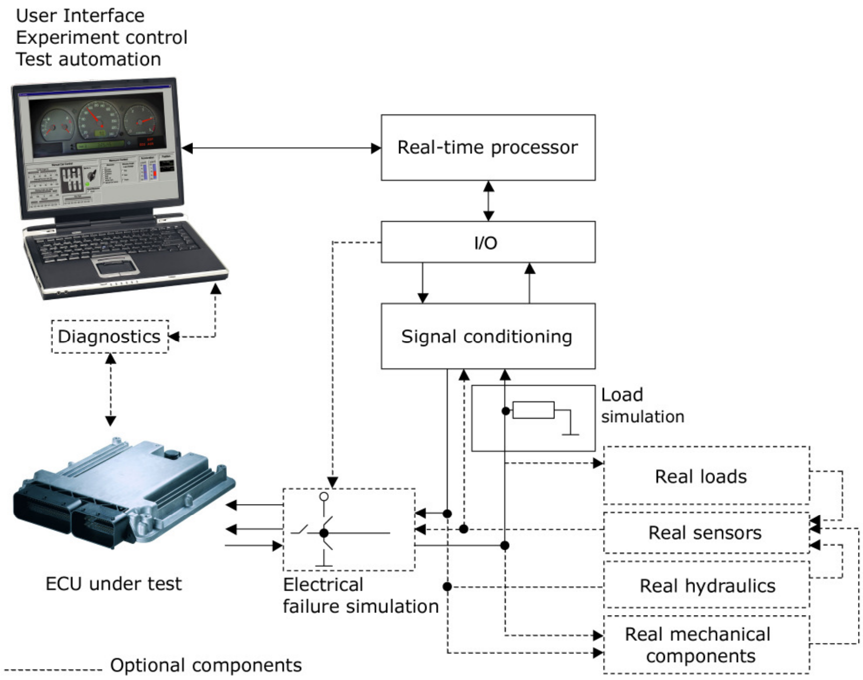

Fig. 2: Components of an automotive HIL system (according to [3])

Hardware Components of an Automotive HIL System

Real-time processors are special boards with optimized I/O interfaces and high-performance multicore processors for fast calculation of plant models. To support VV-HIL systems, the boards are connected to multiprocessor systems. One current VV-HIL utilizes 22 processor cores on six processor boards.

I/O boards and signal conditioning: Automotive HIL applications require boards for simple analog and digital signals, and also special boards for fast, engine-angle-synchronous signals for fast sensor simulation (wheel speeds, knock signals) or actuator measurement. The fast, standard I/O channels are coupled with various special measuring and signal conditioning devices. Examples are highly accurate measurement for determining the quiescent current of the ECU, the resistance simulation of temperature sensors (e.g. PT100), or signal generation for fast sensor actuator control loops, such as oxygen sensor or LVDT distance measurement.

Bus systems: The ECUs form networks and communicate via various bus systems in the vehicle (CAN, LIN, FlexRay, MOST). When parts of the network are operated in HIL, the bus behavior of all the missing ECUs has to be appropriately simulated. Thus, the HIL simulator must be able to *generate* messages (this is called *restbus simulation*) and to *read* all the messages coming from the ECU. Here too, special I/O boards are used, frequently with intelligent subprocessors or FPGAs and suitable bus transceivers.

Electrical loads and load simulation: ECUs control electrical actuators, e.g., valves, electric motors, relays, current-controlled actuators and piezo injectors. The ECU's diagnostic system monitors these actuators for electric faults like short circuit or open wire and for correct dynamic behavior. For these purposes, either loads are integrated into the HIL system, or an electronic (= dynamic) load simulation controlled by the real-time system is used.

Electrical fault simulation: To generate the electrical fault states mentioned above, failure simulation units (FIUs) are often integrated into the HIL system. These can simulate hard short circuits and open circuits, and also leakage resistance and loose contacts. Relays or semiconductor switches are used for this depending on requirements.

Real components are sometimes necessary to treat ECUs realistically. These might be loads that are not easy to simulate or special equipment to measure ECU-integrated actuators or to stimulate ECU-internal sensors. A common example is the measurement of the internal brake valve activation in an ESP ECU with a valve signal detection unit [4].

Software Components of an Automotive HIL System

The software components for an HIL system are subdivided into the implementation and experiment software, and the simulation model.

Implementation and experiment software

In the automotive industry, MATLAB®/Simulink® (ML/SL) has become established as a quasi standard for function development for control systems. It therefore makes sense to use ML/SL both to describe the dynamic behavior of the plant, and to define and configure the I/O of a simulator system, Fig. 3. The entire function and instrumentation code for the real-time system is then generated by autocoding.

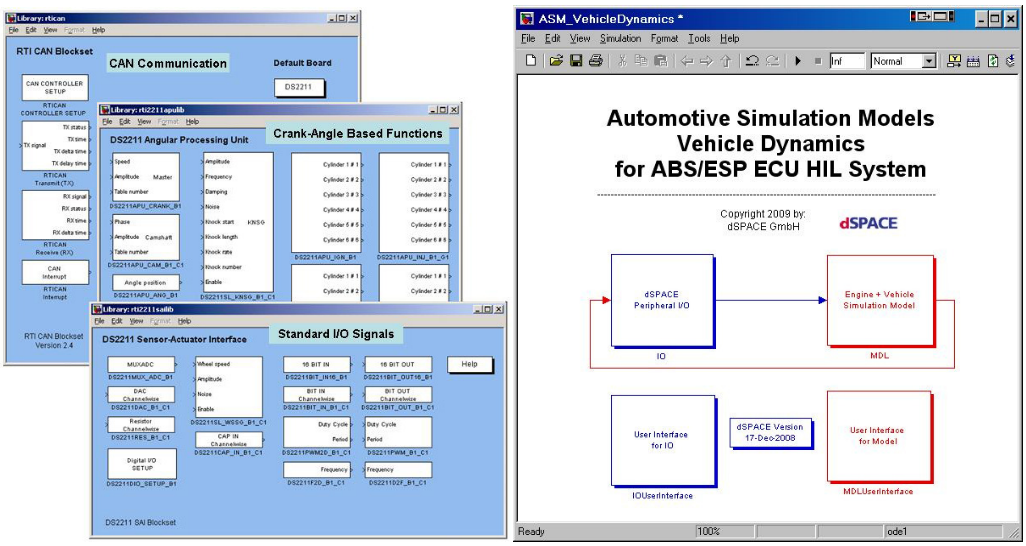

Fig. 3: Simulink® libraries for specifying the I/O of an HIL system and an example model in Simulink®

Interactive experimental operation of the HIL system requires configurable GUIs with a wide range of different views, which can be adapted flexibly to specific projects. Highly configurable instruments and photorealistic layouts help users to work even if they are inexperienced. Automotive test cases require synchronous data acquisition from the real-time system and plotting functionalities. In addition, 3-D visualization is indispensable, especially for vehicle dynamics applications. dSPACE ControlDesk and MotionDesk provide this functionality, Fig. 4.

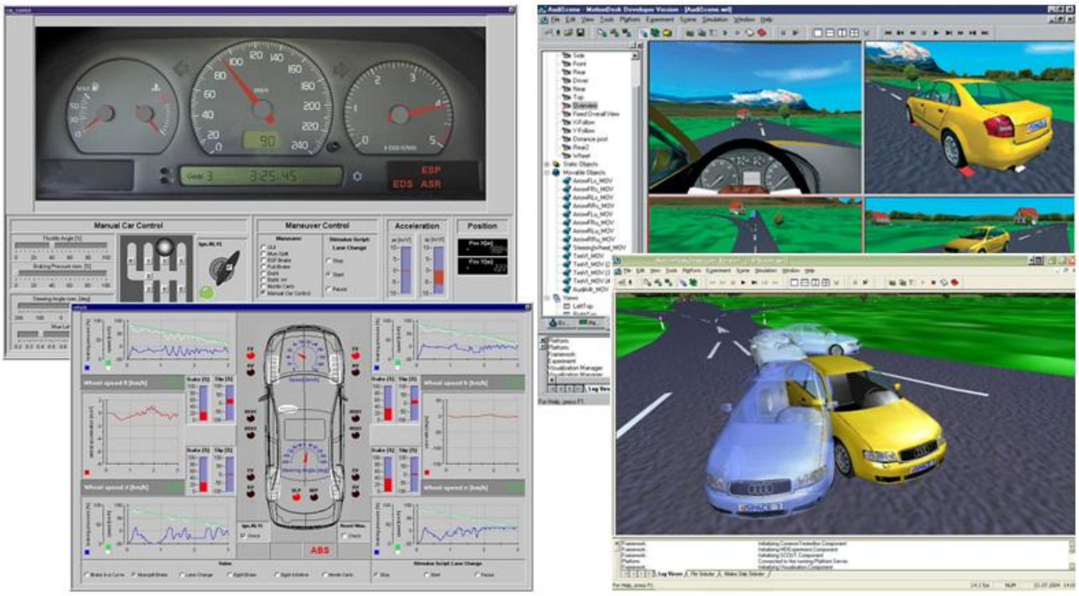

Fig. 4: ControlDesk for interactive operation of the HIL systems and MotionDesk for 3-D visualization [5]

However, the greatest benefit is derived from HIL systems if test runs are not interactive but automated. Script languages such as VBA, MATLAB and Python are frequently used for automation. State-of-the-art test automation tools allow both textual and graphical implementation of test sequences. An example of such a tool is AutomationDesk, Fig. 5. As in Simulink, the test creator can put together a test from single test steps or whole test sequences from libraries, and "program" parallel and serial test sequences. A test management component is needed to help manage test projects, data and results. A debugger helps to speed up test development.

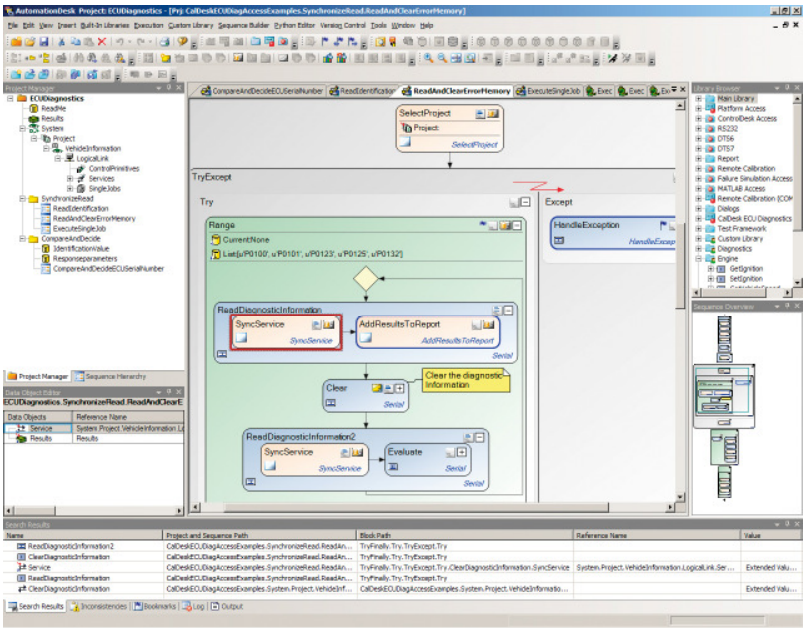

Fig. 5: Graphical programming of HIL tests in AutomationDesk [5]

Automated testing usually is performed by executing tests on a standard PC (host PC) connected to the HIL system. In test cases where greater timing precision is required, real-time testing is necessary. Scripts for real-time testing run on the processor board, i.e., synchronously with the model, so all test actions are performed on a real-time basis.

Simulation model

The simulation model can be divided into the plant model and the sensor and actuator interface, Fig. 3. In an ESP application, the plant model simulates the vehicle dynamics and the environment influences. In the sensor-actuator interface, specific behavior like value conversion from physical to electrical signals and vice versa is calculated. Model structures for fault simulation are implemented. The connection to the I/O hardware and the definition of bus communication are also located here.

Plant models on an HIL test system contain the core information of the system functionality. For running in real-time environments, calculation power is the most limiting factor for model depth and simulation accuracy. The general rule that can be stated for HIL plant models is to model as much as necessary and as little as possible. The model has to be real-time-capable, and it has to ensure enough remaining calculation power for sensor, actuator and bus interface calculations. Automotive plant models simulate highly dynamic processes like in-cylinder combustion or electric motor components. On the other hand, the requirements on model calculation accuracy are low. Because of their mass product character, automotive ECUs themselves have less accuracy, and the model results just have to satisfy the ECU.

With regard to usability, the models should also be easy for inexperienced HIL test persons to understand and use. The structure of Automotive Simulation Models (ASMs) is an example of how model design can help to achieve performance and usability.

Automotive Simulation Models cover the whole area of powertrain and vehicle dynamics simulation for state-of-the-art passenger and commercial vehicles. They contain models and component libraries for combustion engine simulation as well as for vehicle dynamics [5]. ASMs are defined and implemented as open Simulink® models following established structure and parameterization guidelines.

All ASMs are structured componentwise. The ASM components are organized in Simulink® libraries. Each component can be characterized by its inputs, outputs and parameters. Component input and output port descriptions and parameter structures follow certain rules. They include unit and dimension information and additional comments like author or origin. The component implementations are covered with a mask which collects all the component parameters and enables easy access to component descriptions in the documentation, Fig. 6. Each ASM component is connected to the ASM Signal Bus. This bus collects all signals of interest in the model and is the central connection to the sensor-actuator interface.

As already pointed out, parameterization of the plant model is one of the most important preparatory tasks for HIL test system usage. During tests, it is not model modifications but model parameterizations that are necessary. The well-defined parameter structurization described above helps in performing this task. But more intuitive access is required, especially for HIL users who are not familiar with the model contents. For this reason, the ASMs include a stand-alone parameterization tool, ModelDesk. ModelDesk enables the user to define parameter sets from parameter pools, organize them in projects and experiments, and modify parameter values. ModelDesk is completely separate from the Simulink model and supports the parameterization of models on various simulation platforms like MATLAB or dSPACE real-time processors. All ASM parameters are accessible in predefined layouts which reflect the general model structure described above. Custom-specific model parts which are not organized in ASM libraries can be parameterized by import custom Simulink library functionality.

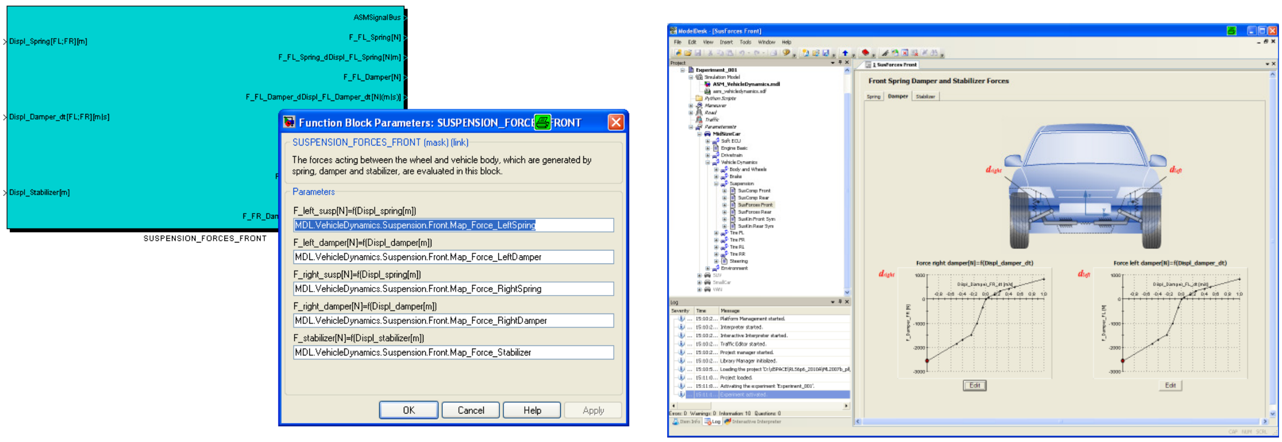

Fig. 6: ASM component Simulink® example and ModelDesk GUI for parameterization

ADDITIONAL REQUIREMENTS FOR HIL TEST SYSTEMS IN SPACE APPLICATIONS

Because space applications have different requirements for test systems, the system structure of automotive HIL systems described above cannot be applied 1:1. The different test philosophy means that other requirements have to be taken into account, and these affect both hardware and software.

In satellite applications, the DUTs are not so complex and the control processes are typically slow. This results in lower demands on the real-time processor, I/O volume and performance. Satellite controllers are not so highly networked as controllers in automotive applications. Thus, the test systems for individual controllers can run more autonomously, and the bus communication traffic for a satellite AOCS test system is not as great. On the other hand, the HIL systems for AOCS are often integrated into a set of SCOEs which are connected to the EGSE controlling all test systems. This overall check-out system itself combines several controller test systems, usually from different suppliers.

Integration into an SCOE results in additional requirements for the AOCS test system. As the goal for the SCOE is to test the entire flight system, as much real hardware as possible is connected to the simulator. This includes real sensors and actuators, as well as mechanical parts like gyros or reaction wheels. Sensors are stimulated via special test connectors, and either real actuators operate in parallel to certain actuator models, or actuators are measured with additional simulator channels.

Another important requirement is to test all the components directly on the flight hardware. This includes tests on shakers and in climate or vacuum chambers. The test systems have to be spatially separate from the DUT for this, which results in relatively long signal connection lines with the effects of noise or differences on GND potentials. Finally, a strong fail-safe design is mandatory for the space HIL simulator.

From the point of view of performance and usability, the requirements of space SCOEs for implementation and experiment software as well as for simulation models do not differ from automotive HIL test systems. The main differences for the simulation model are lower system dynamics but higher accuracy requirements and long-term stability. Considerable differences also of course exist in the plant model content.

DESCRIPTION OF A (d)SPACE HIL TEST SYSTEM

System Structure and Hardware

Fail-safe requirements, spatial separation from the DUT and integration of the HIL test system into an SCOE require a different system structure than that used in automotive applications. The close connection between the real-time processor system and I/O channels is abandoned in favor of distributed I/O modules which are controlled via a galvanically isolated, optical data link from the system, Fig. 7. The small modules can be easily integrated into the engineering and flight models, and A/D or D/A channels are connected with the DUT by short wires. Long distances between the HIL system and modules can also be bridged by the optical connection. Each I/O module is equipped with eight inputs and eight outputs of a certain signal type. Each channel is equipped with an FIU which enables broken cable simulation of actuators or communication buses. Excessive cable length due to connecting in an FIU is avoided.

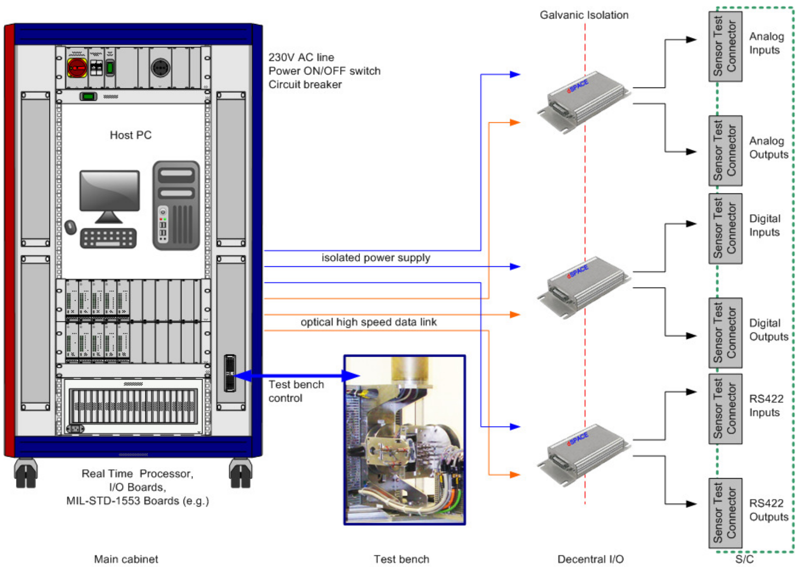

Fig. 7: HIL test system structure for space applications

For nonelectrical sensor stimulation (e.g., optical stimulation of a sun sensor on a turnable rig) or the measurement of actuator activities, mechatronic devices which are not part of the spacecraft (S/C) have to be controlled by the HIL system. In contrast to automotive HIL systems, these test bench components are quite usual in a space HIL system.

Because of fail-safe requirements, the I/O modules perform self tests. The eight inputs are connected simultaneously with the eight outputs. Only after successful completion of the self test are the I/O signals switched to the satellite hardware. During test operation, a repeat self test can be carried out at any time. Testing all channels together takes only a few milliseconds. The connection between HIL test system is connected to the satellite hardware is released by a watchdog circuit. This continuously monitors the communication between the I/O modules and real-time processor, and protects the S/C from undesired signal levels and switching conditions.

A space application has no specific requirements on the real-time processor itself. Due to its limited complexity, a single-processor system, maybe with a multicore processor, is sufficient in most applications.

Simulation Model and Experiment Software

As in the automotive area, ML/SL is a widely used tool for controller development in space engineering, and having the plant models in an ML/SL description is an advantage. dSPACE therefore develops models for AOCS HIL applications in ML/SL according to the implementation rules from the ASMs. The general model and parameter structures are also used.

The plant model for an AOCS application can be divided into three parts: S/C, environment and soft AOCS, Fig. 8. The S/C contains models for the satellite movement itself. The environment covers all external influences on the satellite body, and the soft AOCS is a simple controller which enables the model to run in an HIL environment without closing the control loop by means of the real AOCS hardware.

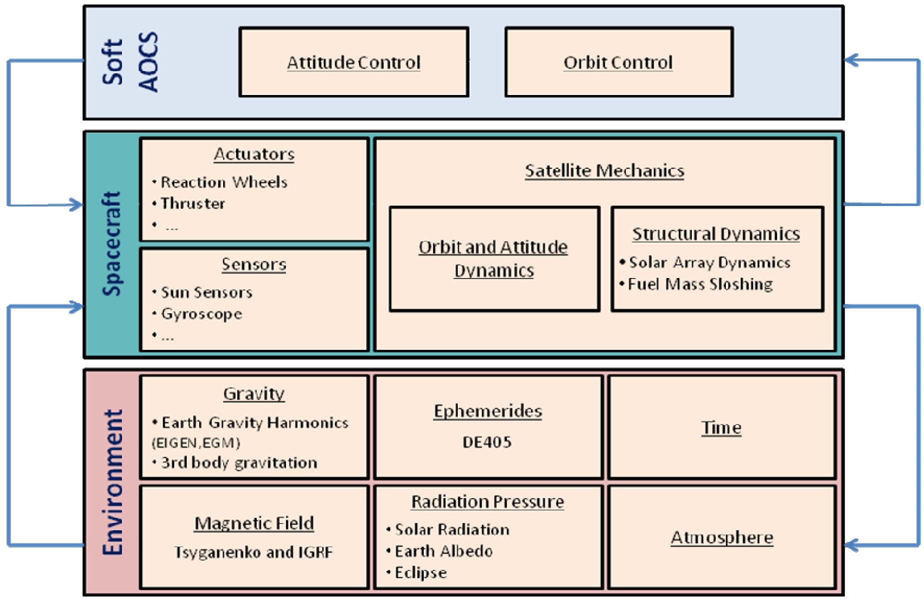

Fig. 8: Plant model structure of ASM Satellite with spacecraft, environment and soft AOCS components

The implementation of the S/C model has some similarities with vehicle dynamics simulation. A passenger vehicle is modeled as a multibody system (MBS) with 24 DoF. The S/C is also modeled as an MBS. It simulates a rigid satellite body with 6 DoF. Connected to the body are two solar panels having 2 DoF each. One DoF simulates the panel rotation, the other the panel deflection. 3 additional DoF in the S/C body are implemented for fuel mass sloshing. The equations of motions are formulated using Lagrangian formalism. This formalism leads to equations in minimal coordinates which can be calculated very efficiently. The main drawback with this solution is its lack of flexibility for integrating additional bodies like reaction wheels. To overcome this, the Articulated Body Algorithm (ABA) is used, which is well known in robotics simulation and also used for the simulation of flexible vehicle-trailer combinations [6]. The S/C model is calculated using quaternions in a reference coordinate system defined in conformity with the IERS conventions and standard epoche J2000, unlike the automotive field where cardan angles in an earth-fixed coordinate system are used.

The simulation of environmental influences is completely space-specific. In an ESP application, a road, driver behavior and surrounding traffic have to be described, while in AOCS test applications, the simulation of earth and planet gravity influences, magnetic field, solar radiation and albedo is necessary. Well-established modeling approaches are available for all the different environmental influences, providing torques and forces on the satellite body system and physical values for sensor simulation.

Sensor and actuator models have similar principles in automotive and space applications, these being mainly look-up tables for value conversion from physical to electrical values and vice versa. The main difference is that real sensors and actuators with test interfaces for stimuli are used in space applications, while in HIL test systems for automotive electronics, the sensors and actuators are simulated. Another space-specific aspect of sensor and actuator simulation is the inclusion of specific erroneous behavior like alignment errors, signal noise and specific measurement and temperature ranges.

As regards test and experiment software, there are not many differences between automotive and space applications. Instrumentation with ControlDesk, S/C movement animation with MotionDesk and plant model parameterization with ModelDesk are still required. One addition is the connection of the HIL test system to an EGSE. This requires additional communication based on SCOS2000. The SCOS2000 interface is implemented in Python, which is dSPACE's standard test automation script language. Python provides standard libraries to implement Ethernet TCP/IP communication. Access to the real-time system of the experiment tools is by means of dSPACE-specific Python libraries.

SUMMARY

A comparison of standard HIL test systems for ESP and AOCS gives a good overview of HIL testing in automotive and space applications. Due to the nature of HIL testing, the general structure is the same in both. The large majority of requirements that apply to automotive applications can be transferred to space technology. Only a limited number of additional requirements arise from the testing philosophy in space applications. We showed that all of these requirements can be met, and proposed satellite-specific hardware solutions and plant models based on existing concepts and implementations. The solutions are available for projects. The ASM Satellite model is currently under development as an off-the-shelf tool.

The whole tool chain has been designed to adapt rapidly to different domains. We therefore expect that with the proposed extensions, a user can easily reuse this well-proven and cost-efficient off-the-shelf framework for different space projects. This has major advantages:

- High maturity and sustainability
- Constant adaptation to state-of-the-art HIL testing technologies
- Knowledge transfer from automotive to space applications
- Very low error rates in the hardware and software
- Excellent usability
- A good cost/value ratio.

In the final analysis, this will improve the overall test quality and at the same time significantly reduce the time needed for the verification and validation of ECUs.

Finally, it might be of interest to potential users that the HIL testing tools are seamlessly embedded in an off-the-shelf tool chain for the entire development process. This means that dSPACE has a complete tool chain to support all development stages from requirements to fully tested product. We believe that it is well worth investigating whether other development tools (e.g., code generators for model-based development such as TargetLink) can also usefully be transferred to the space domain.

REFERENCES

[1] S. Wilhelmi, A. Schmidt: "Elektrik und Elektronik – Komfortsysteme und Leistungsverteilung" *ATZ Extra: Die neue C-Klasse*, April 2007

[2] P. Wältermann: "Hardware-in-the-Loop: The Technology for Testing Electronic Controls in Automotive Engineering" *6th Paderborn Workshop "Designing Mechatronic Systems"* Paderborn, April 2-3, 2009

[3] H. Wallentowitz, K. Reif. (Edt.): "Handbuch Kraftfahrzeugelektronik – Grundlagen, Komponenten, Systeme, Anwendungen" Vieweg Verlag, Wiesbaden, 2006.

[4] H. Schütte, P. Wältermann: "Hardware-in-the-Loop Testing of Vehicle Dynamics Controllers – A Technical Survey" *SAE Technical Paper 2005-01-1660, SAE World Congress*, April 2005.

[5] dSPACE AutomationDesk, Automotive Simulation Models (ASM), *dSPACE Catalog*. dSPACE GmbH, 2010.

[6] K. Liem, M. Peperhowe, H. Haupt: "Modular Multibody Approach for Real-Time Simulation of Vehicle-Trailer combinations" *SAE Technical Paper 10M-0014, SAE World Congress,* April 2010.