Development of Small Satellites, Satellite Subsystems and Components using Dynamic Simulation and Hardware-In-The-Loop Tests

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INTRODUCTION

Since 1993, Astro- und Feinwerktechnik Adlershof GmbH (AFW) offers solutions and services for the aviation and aerospace industry. Besides engineering, precision manufacturing and environmental testing, small satellites technology is a key business segment of our company. In this area, AFW developed the TET-1 (Technologie-Erprobungs-Träger) satellite bus as a platform for various small satellite missions. Furthermore, attitude control components, such as reaction wheels in different sizes and with varying performance, and complete attitude control systems (ACS) incl. the required software for small satellites are part of our aerospace business.

Especially in the field of small satellites, simulation models provide a gainful support due to the mostly reduced financial budgets and tight schedules. The mentioned budget limits make a new model development in each phase almost impossible and moreover not practicable for application and maintenance. Therefore, a substantial library of simulation models, all of which offering reusability and flexibility, has been built up to support the development process in all project phases of satellite missions. The area of application ranges from feasibility studies and concept planning to design and system integration tests. Along with environmental models and the spacecraft dynamics, the model library contains the main spacecraft subsystems and components. All models are implemented in Matlab/Simulink, which makes them independent of specialised and expensive software programs for the different physical domains that are considered.

In addition to extensive simulations, a state of the art ACS test facility was used to evaluate the models and verify the ACS of the TET-1 satellite by tests. The test bed is a combination of a free floating platform on an air bearing, allowing almost frictionless motion of the satellite's ACS model, together with environmental simulation capabilities for the magnetic field and the sun make it a perfect tool to perform end to end tests of the ACS software with the hardware in the loop.

In this paper, techniques and benefits using dynamic simulation models for definition, development and test of small satellite platforms including mission planning, power system analyses and detailed analyses of the attitude control system (ACS) as well as the thermal behaviour of the satellite are discussed and the implemented models are described briefly. Furthermore the simulation environment is evaluated using test data and in-orbit measurements of the TET-1 satellite (launched July, 22nd 2012). The latter are also used to assess the performance of the ACS test bed.

DEVELOPMENT PROCESS

Using advanced dynamical simulation models of components or even whole satellites during early development phases leads to an improved development approach as shown in Fig. 1. With the aid of the gained information about the system behaviour and its performance it is possible to optimize the system design without the necessity for hardware and expensive environmental tests. For detailed designs, components models can be used to analyze and optimise for single functions or parameters before manufacturing and assembling hardware.

The subsequent Hardware-in-the-Loop (HIL) tests allow for extensively testing the interaction between various components and the required software. Especially in the field of ACS development, such HIL tests help avoiding mission critical algorithm failures and significantly reduce the development risk.

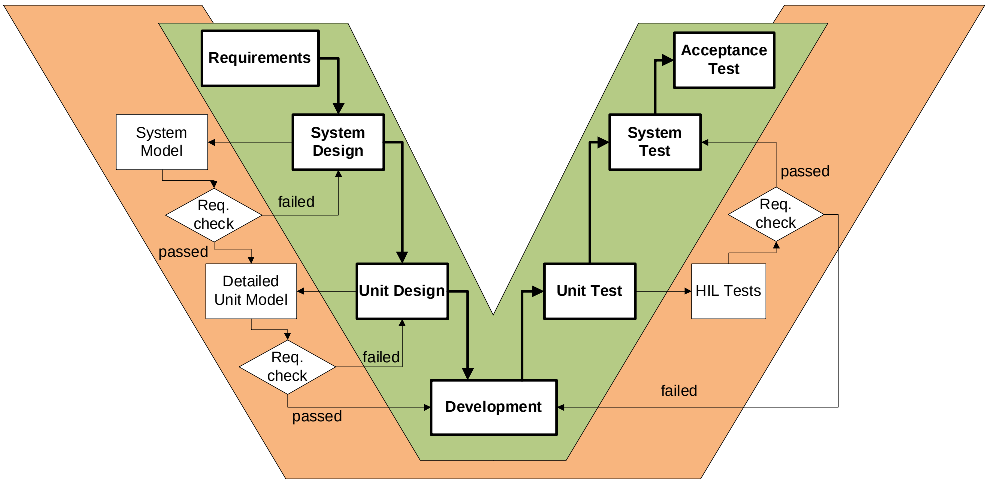

Fig. 1. Extended V model of the system engineering process incl. dynamic simulation and HIL tests

DYNAMIC SIMULATION

The model development process had the objective of highly flexible and reusable models. It is structured similar to the waterfall model known from software engineering and additionally includes the system or ACS engineer technical knowledge and experience. Fig. 2 shows all process stages and their documentation output.

Starting from the problem description, the requirements on the model are defined. The succeeding model analysis forms the core element of the workflow, where the modelled system and its mathematical representation in natural language and equations are described. The phase’s output, the (platform-independent) knowledge model, ensures that all functional and non-functional requirements are met and the model’s content is well conditioned and understandable. A lack of documentation in this phase is often hindering reusability or making external models useless, because important information on constraints or knowledge sources are missing and therefore result in mistrusting the model’s correctness.

The analysis is followed by the design stage, which defines interfaces and the model’s internal structure. This definition is still kept on an abstract level in a modelling language such as SysML and therefore the model is still platform-independent and reusable for different modelling environments at this stage. In the implementation phase, the model’s source code is written in the target language or model environment, whereat modelling guidelines and code documentation respectively assure understandability and thus reusability of the model. Finally, the validation document describes test patterns for the model to verify the implementation.[1]

The practical capabilities of the model development process were proven by setting up a dynamic simulation model of the TET-1 satellite bus, which was implemented in the Matlab/Simulink environment. Due to a high degree of modularization, all features and subsystems can be recombined easily to extend the model library. The satellite model, its thermal model extension and an example of a detailed component model are presented in the following section.

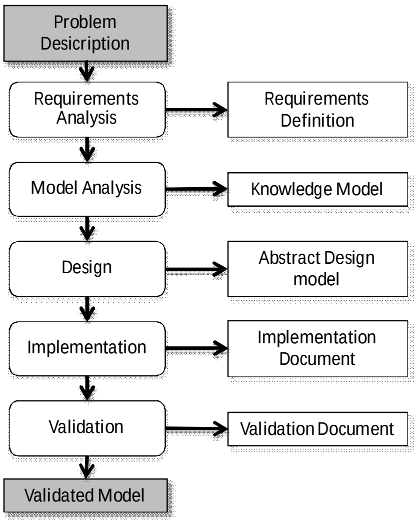

Fig. 2. Collaborative model development process [1]

The Spacecraft and it’s Environment

The model describes a closed loop simulation of a satellite bus basing on the TET-1 satellite bus and its interaction with the environment. On the top-level view, as shown in Fig. 3, the model consists of four major elements: environment, satellite, dynamics, and mission. The environment sub-model considers the satellite’s orbit based on the SGP4-theory [2] and all relevant space objects and their influences according to ECSS standards [3], whereas the mission block introduces the start time of the simulation and therewith defines the satellite’s mission time.

The “Satellite” block describes the internal configuration and subsystems, power, and attitude control of the satellite. The interoperability of the satellite subsystems is given by well-defined interfaces and thus enables the integration into a complete spacecraft model. The dynamics block formulates the interaction between satellite and space environment, i.e. the equations of motion and three-dimensional disturbance torques induced by, for example, the magnetic field of the Earth. [1]

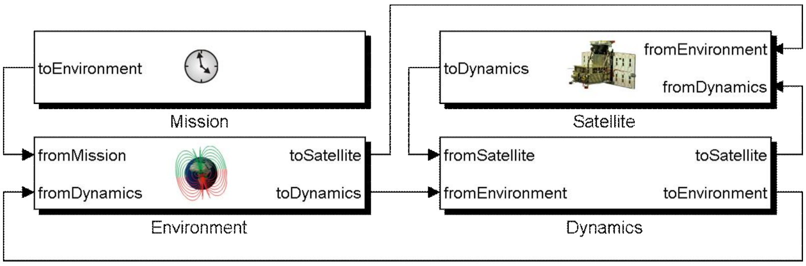

Fig. 3. Satellite model including mission information, environment, and dynamics [1]

Thermal Model

The sub-model "Satellite" described in the previous section only includes simplified thermal properties of some satellite components and therewith leads to limited thermal analysis capabilities. In order to receive reliable temperature profiles of the satellite and its components, a more detailed thermal model has been developed for MATLAB.

The thermal model of the satellite is also implemented in a modular way, i.e. the structure, components and their thermal and mechanical properties can be arranged according to the considered satellite design. The algorithm takes

- thermal conduction,
- thermal radiation, and
- thermal heat sources

into consideration. The resulting system of differential equations is solved using the finite volume method. In Fig. 4 (left), an example of the thermal representation of part of a satellite is given.

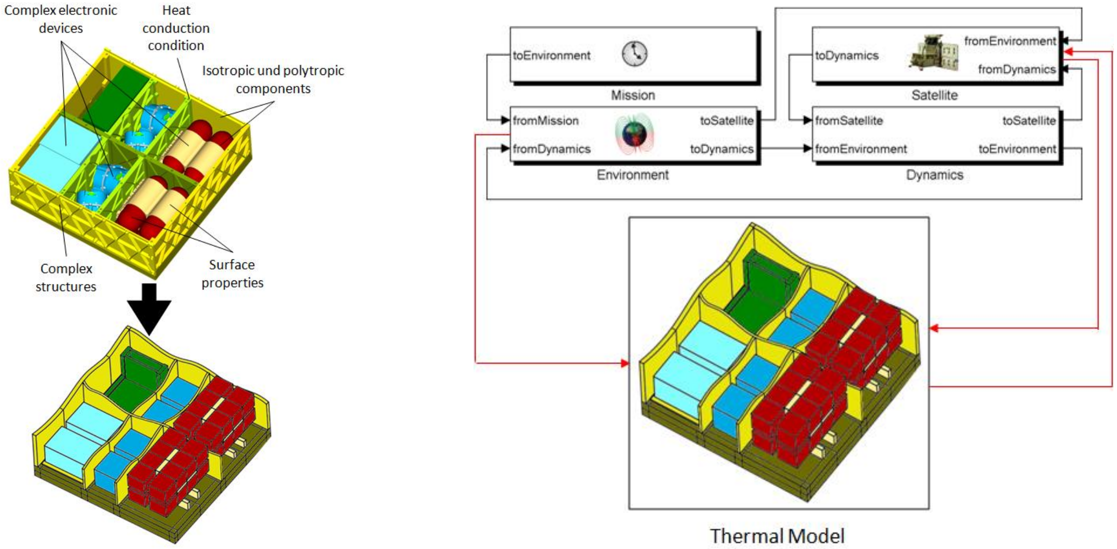

Fig. 4. Example for thermal model of parts of a satellite (left) and integration of the thermal analysis of the satellite [4]

The thermal behaviour of the satellite mainly depends on various parameters, such as external heat sources due to Sun and Earth radiation, internal heat sources due to electric power consuming devices, space environment as a heat sink, and thermal properties of the satellite. It becomes obvious that only considering the thermal model of the satellite does not yield reliable results. Also the satellite's environment, i.e. its orbit and actual position/attitude, and the mission operation, i.e. operation of the single consumers inside the satellite, need to be considered. Furthermore, the temperature of the satellite subsystems and components can have an influence on their performance and therewith on the satellite operation. Hence, the thermal algorithm should be coupled to the satellite model described in the previous section, refer to Fig. 4 (right). [4]

ACS Components

During the last years, detailed component models turned out to be more and more requested by our customers, in order to evaluate and improve their system performance at an early design stage. Furthermore, these models yield a good basis for analyzing and improving the components themselves. Therefore, detailed models of AFW's reaction wheels (RW) have been implemented in SIMULINK to analyse the dynamic behaviour of the wheels and the whole satellite.
The developed RW models provide all relevant physical and telemetry data to the user and include the following features:

- Motor model including Back-EMF, coil inductance and iron, Ohmic and friction/stiction losses,
- Power model to determine the measured current and voltage taking the electronic losses into consideration,
- Sensor Model representing the optical encoder,
- Software Model (program block) including controller, determination of the telemetry data and the state estimation

The Simulink-Model of a reaction wheel is depicted in Fig. 5. These models are described in more detail and are evaluated in [1] and [5].

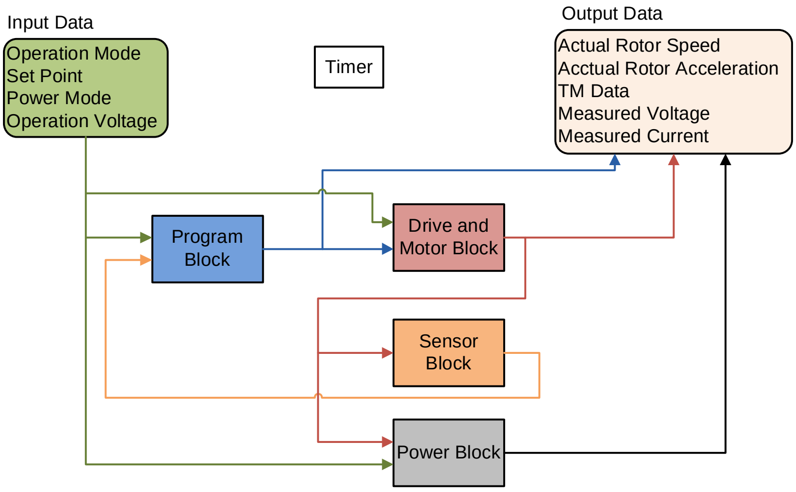

Fig. 5. Block diagram of the reaction wheel model

Hardware-In-The-Loop Tests

In addition to detailed simulation during the development process, HIL tests are a valuable mean to determine the actual (sub-) system performance and to extensively test software algorithms. The most critical task for on-ground testing is an adequate simulation of the orbit environment.
For the verification of the attitude control system of TET-1 on ground, a special test stand was used. The test facility consists of a magnetic field simulator, a sun simulator and an air bearing platform. The platform represents the satellite bus and its moments of inertia can be adjusted to the specific characteristics of the simulated satellite. Its ACS components and onboard data handling system (OBDH) can be integrated and utilized on the platform. The platform itself supplies the bus (ACS components and OBDH) with a wireless communication system and power via a battery stack. Hence, an almost undisturbed test environment has been achieved.[6]

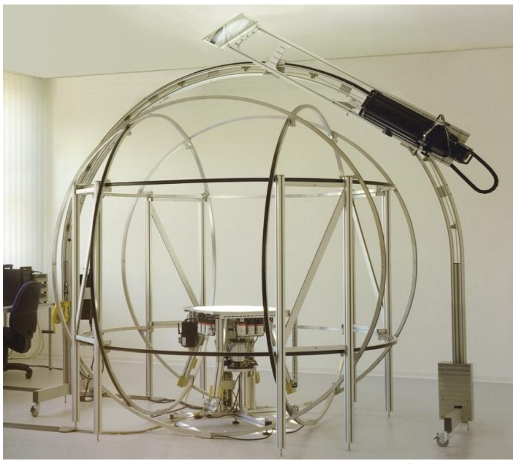

Fig. 6. AFWs attitude control test facility

MODEL AND TEST FACILITY EVALUATION

Since TET-1 is in orbit for almost three years, a large data base is available for comparing in-orbit data with simulation and test results. Thus, model and test facility evaluation and adaptations are possible, in order to improve the on-ground simulation and test capabilities for future projects. In the following, some examples for the model and test bed evaluation and correlation with in-orbit measurements are given to show the model quality.

Evaluation of the Dynamic Simulation Models

Satellite Motion and Slew Manoeuvres

As already mentioned, the ACS and its components are a key business of AFW. Therefore, the detailed analysis and evaluation of this subsystem and the corresponding dynamic models are of importance for future projects. In the following, a mode change of the satellite will be discussed incl. satellite rates and their noise performance.

Usually, TET-1 is operated in sun pointing mode, in order to provide sufficient electrical power for the satellite bus and the payloads. During the current mission phase, the multispectral camera on TET-1 is used for fire detection on ground. For that purpose and for data downlink, earth pointing manoeuvres and high measurement rates are necessary. In Fig. 7, a typical mission scenario is plotted. When comparing the satellite rate measured on TET-1 to simulated values, it becomes obvious that the system dynamics and even the noise performance match very well (refer also to Table 1).

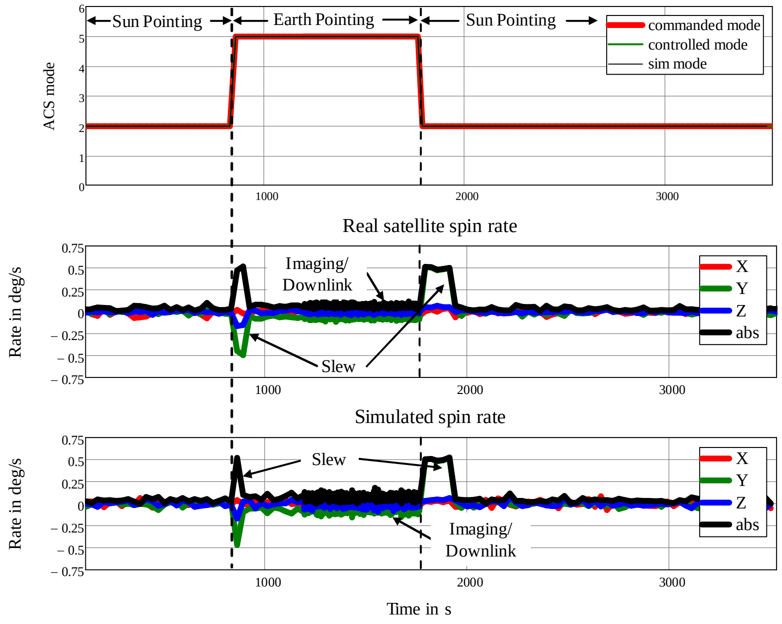

Fig. 7. Attitude modes (top), TET-1 satellite spin rate (middle) and simulated spin rate (bottom)

Table 1. Mean satellite rates and standard deviations (RMS) for in-orbit data and simulated values

		TET-1 satellite rate (deg/s)	**Simulated satellite rate (deg/s)**	**Deviation (deg/s)**
Mean value	**X axis**	0.0010	-0.0018	0.0028
	Y axis	-0.0637	-0.0639	0.0002
	Z axis	0.0004	0.0013	-0.0009
RMS (1σ)		0.0153	0.0249	

As sun pointing is the mostly commanded attitude mode, in Fig. 8 the real and calculated sun vector are compared with each other. Generally, it can be seen that the pointing requirement of 5 arcmin (1σ) is kept by TET-1. The standard deviation between real and simulated value is 1.37 arcmin (1σ), which is considered to be very accurate. When taking into account that the standard deviation between ideal and real Sun vector is 1.32 arcmin (1σ) the quality of the simulation can be rated even higher.

Spikes as shown at 600 s can be caused by various factors such as the onboard software or hardware errors. Such effects will be investigated more detailed in the future to get a deeper understanding of the system behaviour and to further improve the simulation environment.

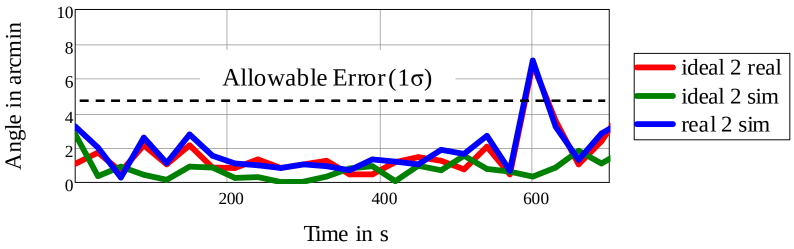

Fig. 8. Deviation of Sun vector between ideal, real and simulated data

Thermal Behaviour of Satellite Components

As an example for the validation of the thermal model, the temperatures of two transmitters (TX1 and TX2) are given in Fig. 9. The peaks indicate operation of the corresponding transmitter. Since TX1 (red lines) is only included for redundancy, it was not switched on. The temperature variations between the transmitter operation are caused by the eclipse phases in orbit. This effect can only be simulated by coupling the satellite model (incl. orbit environment) and the thermal model. Comparison of in-orbit data and simulation results yield the conclusion that they match very well, especially for TX2.

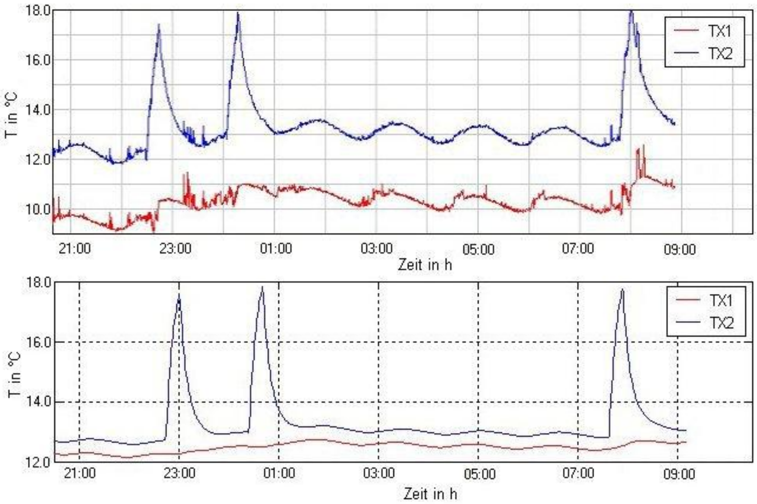

Fig. 9. Comparison of in-orbit (top) and simulated (bottom) transmitter temperatures [5]

Evaluation of the ACS Test Facility

For evaluating the ACS test stand performance, also a slew manoeuvre is analysed, since it is supposed to be a good measure for the overall dynamic behaviour of the ACS and the performance of the test bench. Here again, a slew between sun pointing and earth pointing is considered, refer to Fig. 10.

When comparing the slew to the ones depicted in Fig. 7 it can be seen that the system dynamics are represented quite well by the test bed. Furthermore, analyzing the signal during earth pointing the standard deviation of the platform rate is approximately 0.019 deg/s (1σ) and therewith matches the noise performance of TET-1. Since the test bed measurement rate was 0.5 Hz (and not 2 Hz as for the simulation and the in-orbit data), the noise behaviour on the test bed is slightly underestimated.

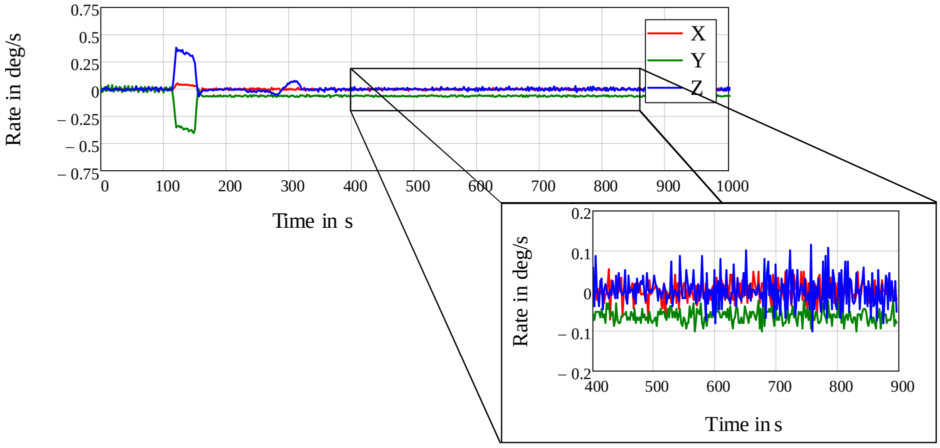

Fig. 10. Satellite spin rate measured on ACS test bed

CONCLUSIONS

The dynamic simulation of the whole satellite incl. its interaction with the environment and detailed component models has been proven to be a gainful support during the design process. The tool can be used for analyzing dedicated aspects such as satellite motion and power budgets and even performance analyses on component level, e.g. star tracker blindings and reaction wheel operation. In this paper, it is shown that the models implemented match real orbit data very well and therewith yield an excellent basis for designing future satellites, subsystems or components.

In addition to extensive simulation, HIL tests have been used to develop, optimize and verify the TET-1 ACS. Now it could be shown that the received test data represent the behaviour of the ACS in orbit quite well. Hence, the developed test bed will be reused for other ACS developments in the future.

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