HIGH PERFORMANCE SATELLITE DYNAMICS AND CONTROL SIMULATION FOR MULTI-PURPOSE APPLICATION

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Abstract: *In a collaborative research effort between the German Aerospace Center and the Center of Applied Space Technology and Microgravity, University of Bremen, the high performance satellite dynamics simulator (HPS) is being developed. The simulator is assembled as a library of simulation modules, functions and utilities, thematically grouped into sub-libraries. The single sub-libraries contain modules for dynamics, environmental models for the calculation of gravity, atmosphere, magnetic field, solar pressure, eclipse, ephemerides, and preprocessing tools for the pre-calculation of surface forces and torques. A transformation library including date and coordinate transformations and several mathematical functions are also provided. Furthermore, a basic set of simple actuator and sensor models is being developed. All modules can be used in MiL (model-in-the-loop) and SiL (software-in-the-loop) applications, and several modules are ready for use in HiL (hardware-in-the-loop) environments. The simulator project has emerged from the desire to avoid re-development, benefit from tools that are already in use and have been validated for recurring problem statements, and build up upon existing knowledge for new challenges. This paper describes the simulator library content in detail and exemplifies application for selected use cases.*

Keywords: *spacecraft simulation, AOCS modelling, disturbance preprocessing, HPS.*

1. Introduction

Years of experience in the areas of AOCS component development, general subsystem studies, generation of end-to-end mission simulators, (subsystem) testing and verification, has led to a large set of simulation software tailored towards a wide range of applications. In order to benefit from past efforts for future challenges and avoid re-development, a project has formed to generalize applicable heritage software and new additions as much as possible to enhance reusability, thereby shortening future development cycles. In collaboration with the Center of Applied Space Technology and Microgravity (ZARM), University of Bremen, the GNC Systems department of DLR (the German Aerospace Center) develops the high performance satellite dynamics simulator (HPS) for application to a wide range of missions pursuing different objectives. The simulator is assembled in a modular fashion. The modules include simple and multi-body dynamics, and environmental models for the calculation of gravity, atmosphere, magnetic field, solar pressure, eclipse, and ephemerides. Furthermore, preprocessing tools are provided for the pre-calculation of surface forces and torques. A transformation library including date and coordinate transformations and several mathematical functions are also part of the simulator. Finally, a basic set of simple actuator and sensor models is being developed.

2. Simulator Overview

HPS is a useful tool for every engineer that is involved in guidance, navigation, and control. The focus during the development of HPS is based on an approach to support the full system life cycle from MiL, SiL, and HiL, to post-processing data. It is a combination of simple and advanced models which allow a tailoring toward the user's needs. Due to the fact that every part of HPS is developed with respect to a full quality assurance process, including comprehensive verification, HPS is gaining relevance inside and outside DLR and ZARM. At the moment HPS is in its beta phase, where it is extensively tested and verified through several projects and missions inside DLR and ZARM.

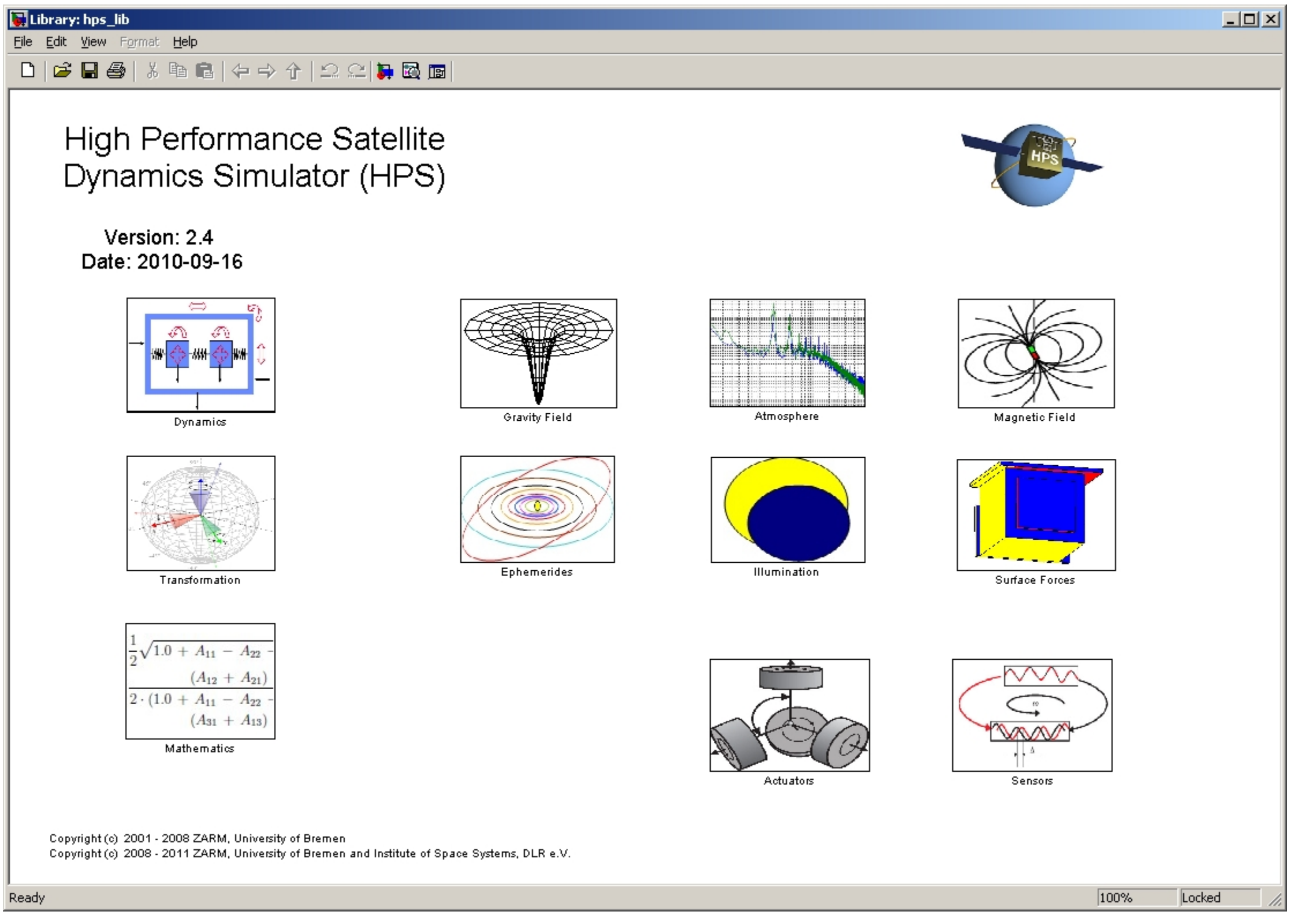

Figure 1. The High Performance Satellite Dynamics Simulator

HPS is arranged as a MATLAB/Simulink library. Apart from the user interface, most models are coded in (embedded) MATLAB/Simulink or C/C++ called via Simulink s-functions. The HPS library is shown in Fig. 1.

2.1. Dynamics Library

The simple satellite dynamics model can simulate a six degrees of freedom rigid body. With the additional input of an accumulated angular momentum, it is even possible to handle a set of reaction wheels. Due to its simplicity, SiL and HiL applications for, for example, controller design are very feasible with this model.

The multi-body satellite dynamics allows for in-depth investigation of complex dynamics including instrument-spacecraft coupling. To a certain degree, flexible structures and sloshing can be accounted for through the modelling of multiple bodies and coupling interactions. The dynamics library can also be used for swarm structures by running multiple instances of the dynamics module at the same time. The multi-body dynamics core is highly accurate due to its completeness in accounting for dynamical and environmental effects. High-precision gravity models, which are also available as stand-alone modules, are included inside the multi-body dynamics such that the gravitational acceleration gets updated at every internal time step. Other external disturbances due to environmental effects get accounted for only at every external time step, which is set by the user. Typical outputs of the multi-body satellite dynamics are attitude rate, quaternion, position and velocity for the spacecraft and specified subsystems. For post-processing purposes additional outputs for coupling interaction, gravity-gradients and external disturbances can be enabled.

2.2. Environmental Libraries

The gravity library contains a simple model for the calculation of gravitational acceleration and gravity gradients up to Earth spherical harmonic field degree 6. Two higher order models up to degree and order 360 (customizable to higher order for the Earth Gravity Model 2008) with different singularity treatment are also available. For the standard modelling approach singularities exist at certain points. One (actually two) of them concerns the computation along the axis through the poles. There, several functions of the calculation routine tend to infinity. This is a numerical problem and does not represent the modelled nature. In the following, a solution is presented dealing with singularities in the conventional gravity model based on [6].

The solution applied here is the replacement by values found across a circle with a so-called singularity radius. For the pole singularity at x = y = 0, [x, y ,z] referring to ECEF (Earth-Centred Earth-Fixed) coordinates, the z-axis pointing towards the pole, this radius appears to be determined by the absolute relative distance [x, y]/R less than the numerical precision limit, where R is the Earth radius. Below that limit, the gravitational acceleration jumps to unphysical values. At x = y = 0 it is obviously NaN. Between the point of jump i.e. the singularity radius, and the singularity itself, the value calculated for the gravity acceleration is somewhat constant but false. The actual gravity acceleration at the pole can be retrieved by interpolation between the values for the gravity acceleration on the singularity radius as shown in Fig. 2 (for clarity of illustration, y = 0 and x is varied).

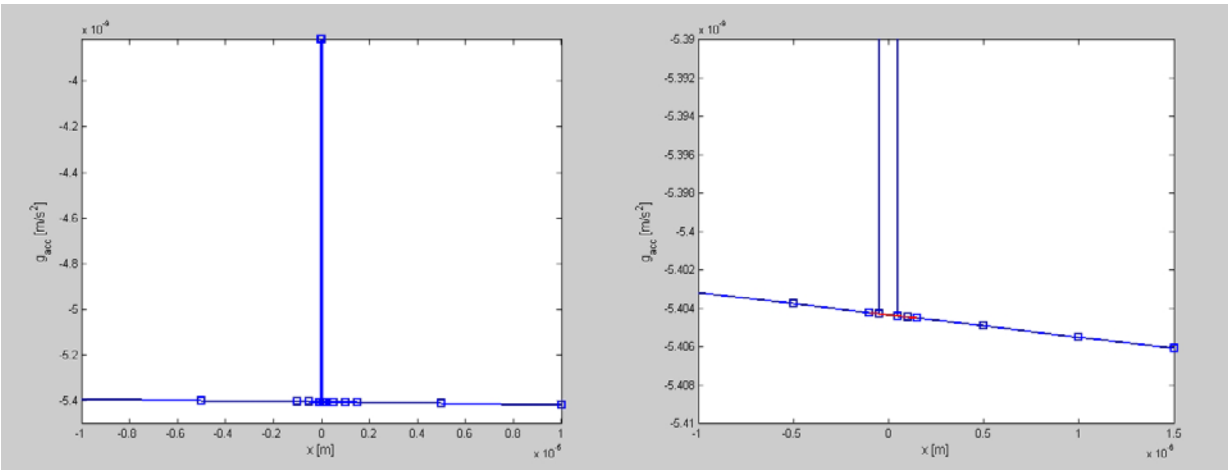

Figure 2. Gravity model singularity treatment, left: Unphysical jump close to the singularity, right: Zoom with interpolation line (red).

A second model implemented uses the method of Pines with the formulation presented in [8], and avoids the singularities entirely. According to [8] the method of Pines however is affected by an intrinsic loss of precision at the equator. In thorough testing, it has been found though that both formulations perform more than adequate for commercial as well as scientific application.

The care taken with respect to gravitational modelling for the main application of spacecraft in Earth orbit reflects gravity as the main motion driver. For the inclusion of other environmental disturbances it is mainly relied upon existing models largely following ECSS standards [7]. For several models a few adaptations have been necessary, including interface generation to allow access from the HPS library as a unifying framework. Adaptations have been carried out respecting licence and copyright restrictions.

The atmosphere library contains the Harries-Priester, the NRLMSISE00, and the HWM93 wind models. In addition, a module for calculation of atmospheric indices required by the NRLMSISE00, and the HWM93 wind models, is provided. The Harris-Priester density model is a quite simple model to determine the mass density of the upper atmosphere at a given point. The implementation within HPS follows a description inside [14]. NRLMSISE00 has been released by the US Naval Research Laboratory. It is an empirical model for the atmosphere extending from the ground to the exosphere and models the temperatures and densities of the atmosphere's components. It is recommended by [7] to use the NRLMSISE00 for altitudes below 120km for calculating total air density, while the Jacchia-Bowman model [2][3] shall be used for higher altitudes. The Jacchia-Bowman model is valid from an altitude of 120km to the exosphere. Within that range, according to [7], it provides a better and more accurate model representation of the mean total density, compared with the NRLMSISE00. Currently development of an interface and a module for indices preparation is under way to enable the use of the Jacchia-Bowman model within the HPS framework.
HWM93 (Horizontal Wind Model, released in 1993) is an empirical global model of horizontal winds in the middle and upper atmosphere. Its derivation is based on accumulated measurements obtained from satellite data, radar, and ground-based optical remote sensing.

The magnetic field options are the IGRF11 and the Tsyganenko models. The International Geomagnetic Reference Field 11th generation (IGRF11) released by the International Association of Geomagnetism and Aeronomy (IAGA) is a standard mathematical description of the Earth magnetic field and has been established as a product of a collaborative research effort between magnetic field modelers and institutions involved in collecting magnetic field data from various sources. Updates for this model at DLR mainly target to enable usage with HiL application.
The Tsyganenko models are semi-empirical best-fit representations for the magnetic field, based on a large number of satellite observations and including contributions from major external magnetospheric sources. Preparation of the Tsyganenko models for use with the HPS suite is currently underway.

The illumination library includes models for eclipse, solar radiation pressure, and albedo. The eclipse module determines if an object orbiting a central body is shadowed by the central body considering total, partial, annular or no eclipse. Solar radiation pressure can be calculated using a simplified expression based on a point source. A correction can be applied accounting for finite disk dimensions of the source. The albedo model is based on [1]. Extensions have been developed e.g. for inclusion of OMI (Ozone Monitoring Instrument) data. Currently the albedo model is newly setup with alternative algorithms to speed up computation time and account for multidirectional disturbance vectors in low Earth orbit.

2.3. Preprocessing

The detail to which surface forces and torques are modeled can be decided individually. For a rough estimation, this may be based on a reference area. More accurate results will be achieved with a geometric model of the satellite that is discretized into finite elements with given surface properties. In preprocessing, element forces and torques can be calculated for specified conditions. For example, for solar radiation, illumination conditions can be determined based on incident sun angle. For illuminated areas, element forces and torques are computed and summed to get the total force and torque. A tool for lookup table creation allows normalized total forces and torques for different conditions to be saved for use in a closed-loop simulation. Figure 3 shows the main preprocessing GUI used for that purpose.

Figure 3. The surface forces and torques preprocessing GUI

The preprocessing GUI also allows the calculation of an orbit- and attitude-dependent reference cross section to be used for calculation of environmental forces and torques based on a simplified formula. Furthermore, in a preliminary check, the correct conditioning of any supplied geometric satellite model can be investigated. For that purpose, the satellite is “illuminated” from six perpendicular directions, simulating the disturbance direction. The illumination conditions are displayed for all directions where the color-coding is as follows: An area subjected to the disturbance is shown in yellow, areas shadowed by other elements are colored in red and back faces or elements not exposed to a disturbance are shown in blue.

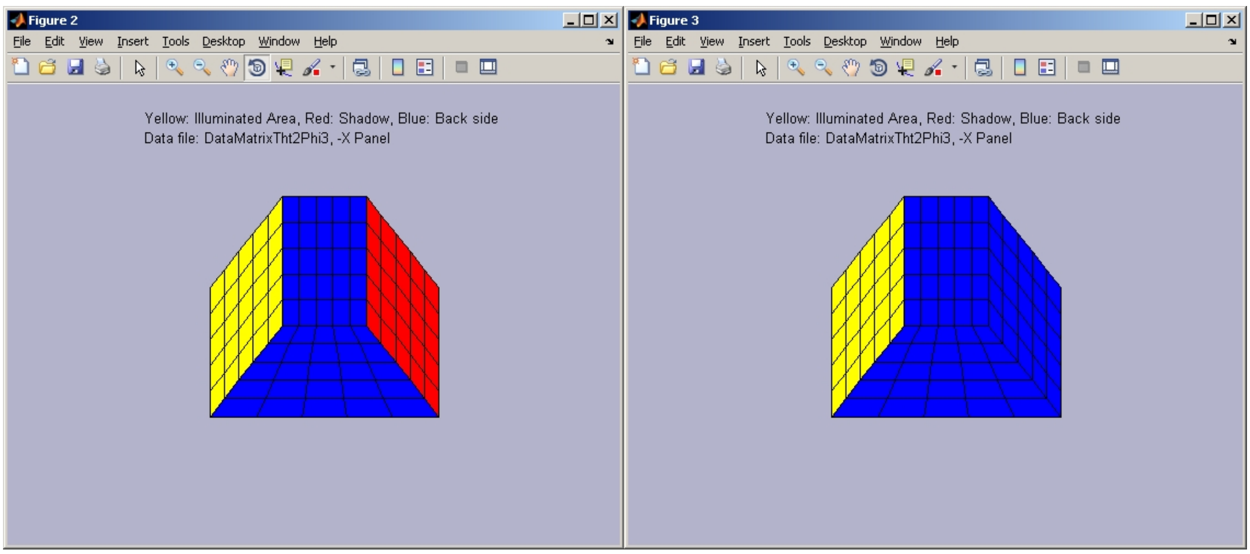

Figure 4. Normal vector orientation check. Left: Wrong orientation, right: Corrected

Figure 4 shows an illumination check for a simple geometry. The model delivered exhibits wrong normal vector orientation for one of its surfaces; an area that should have back-faced elements for the given illumination condition is identified as shadowed. This is not surprising since common CAD software cannot distinguish between outward- and inward-facing surfaces. With the aid of a function developed for that purpose, the normal vector orientation is flipped for the elements affected. This correction is shown in the right part of Fig. 4.

With the geometric model conditioned properly, the main task of calculating normalized surface forces and torques can be carried out. An angle range can be specified with desired accuracy, i.e. angle increment. For a full simulation cycle where the satellite attitude is not fixed it is advisable to specify start and end points covering the full angle range. The normalized surface forces and torques are tabulated for access during the actual simulation based on satellite position and attitude with interpolation/extrapolation for intermediate points between angle increments. Figure 5 shows a normalized force distribution for the example geometry from Fig. 4. Using the preprocessing GUI for the computation of disturbances due to solar radiation, by multiplication with the calculated solar radiation pressure during simulation, the actual disturbance is obtained. This principally applies to all environmental specific element surface forces and torques that can be expressed using an equation like

$$\underline{f}_{\mathrm{i}} = -A_i[(1-\mathrm{c}_{\mathrm{si}})\cdot\underline{\mathrm{e}}_{\mathrm{dist}} + 2(\mathrm{c}_{\mathrm{si}}\cos(\alpha)+\frac{1}{3}\mathrm{c}_{\mathrm{di}})\cdot\underline{\mathrm{e}}_{\mathrm{N}}]\cos(\alpha) \quad (1)$$

where A_i is the element surface area, $\underline{\mathrm{e}}_{\mathrm{dist}}$ and $\underline{\mathrm{e}}_{\mathrm{N}}$ are the disturbance and normal unit vectors, α is the angle between them and c_{si} and c_{di} are material coefficients; for solar radiation they represent the coefficients of specular and diffuse reflection respectively.

For the calculation of Albedo-induced disturbances, for spacecraft in near-Earth orbit, the difficulty arises to account for several instead of one disturbance vector direction. Currently a simplification is applied compromising between acceptable accuracy and computation time, but work on a more efficient scheme is in progress.

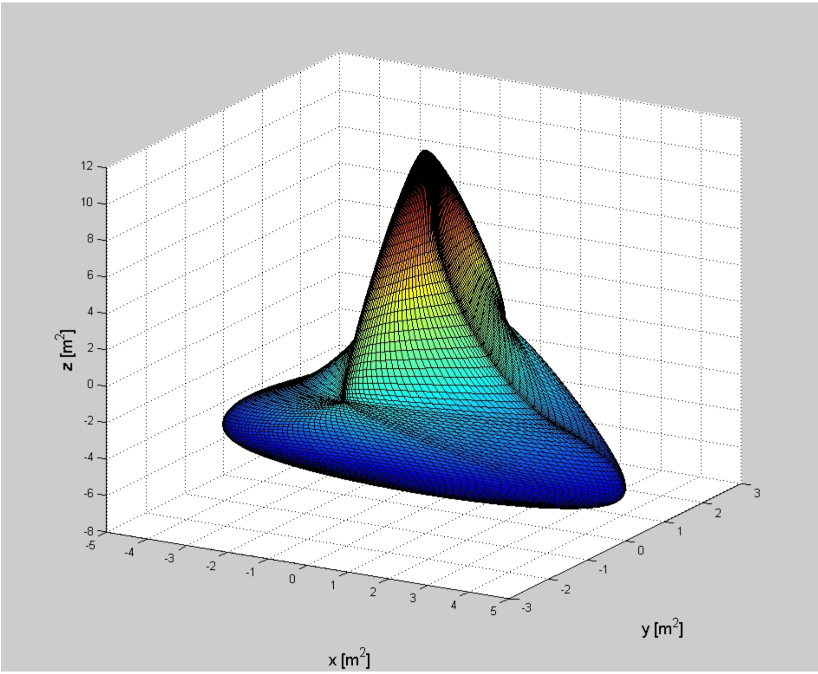

Figure 5. Example normalized force distribution

A second preprocessing tool targets Albedo input data preparation for the calculation of a mean Albedo irradiance based on TOMS (Total Ozone Mapping Spectrometer) or OMI data sets; both can be retrieved from [19]. Next to the default monthly mean reflectivity data sets provided, custom data sets can be generated or processed based on satellite data. The tool takes over data formatting, averaging for multiple files, gap filling and shows an animation of the averaging process if desired.

2.4. Sensors and Actuators

For attitude determination and control, sensors and actuators are used on board of a spacecraft. The design goal for HPS is to include a functional model of every typical spacecraft sensor and actuator. To apply these models the users need only to parameterize the models to reflect their own systems. The sensors and actuators libraries are currently under development with a few models already fully integrated and tested. The following will give an overview of the models and their origin.

2.4.1. Star Tracker

For high accuracy attitude determination a star tracker is a common sensor system with accuracies that go down to arcseconds. Star trackers observe the stellar background and take images of the sky. These images are processed to identify the brightest points on each image and determine their relative distance between each other. The distance information is compared to an onboard star catalogue to identify the exact attitude of the satellite. Due to its complexity of optics, computing power and mechanical design star trackers belong to the most expensive attitude sensors. Nevertheless they are state of the art sensors onboard of spacecrafts and satellites for inertial navigation.

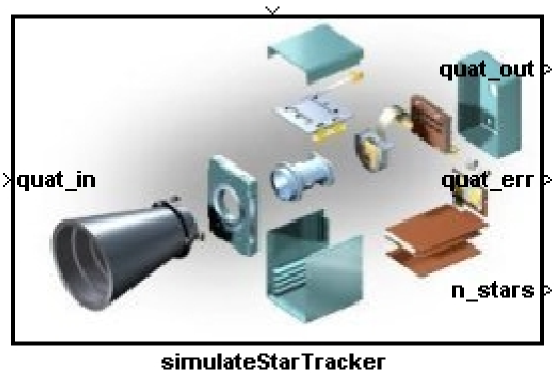

Figure 6. Matlab/Simulink model interface of the HPS star tracker

Inside HPS a Simulink star tracker model, see Fig. 6, is included which is already used for the SHEFEX 2 [15] and AsteroidFinder/SSB missions [11], the latter is shortly introduced in section 3. The mathematical model of the star tracker is based on the noise model in [17].

The Simulink star tracker model represents a star tracker with one single camera head. It can be parameterized by the camera’s field of view, the star magnitude threshold, a mounting quaternion and a star tracker accuracy. The underling model is based on the pin-hole camera principle. The model takes the inertial attitude quaternion with respect to the Earth Centered Inertial (ECI) frame as an input. If there are no disturbances this inertial quaternion would be the ideal output of the star tracker model. With the input and the mounting quaternion the stellar background of the current field of view is generated inside the model. The data base for the stellar background is the HIPPARCOS star catalogue. From the star catalogue a virtual image is generated as it would be observed on board of a satellite. This virtual image is passed to an attitude determination algorithm, which uses Davenport's q-method [20] and the resulting quaternion is passed to the output. Additional outputs are the error quaternion and the number of stars that were detected.

2.4.2. Inertial Measurement Unit

An inertial measurement unit (IMU) is the combination of accelerometers and rate gyros. If at least three orthogonally arranged accelerometer and rate gyro pairs are used an inertial navigation is possible, without measuring an external reference. To find a navigation solution only the initial state has to be known and the measurements of the IMU have to be integrated. HPS includes a functional IMU model, which was developed for the SHEFEX 2 mission. The HPS IMU model is based on [4], where the mathematical background is stated. The IMU model provides high rate measurements of the system dynamics. It reads in the true vehicle dynamics, corrupts these values with various error sources, integrates the corrupted values and outputs the back differences as the measured outputs. For both the accelerometers and gyroscopes, the model takes into account maximum rate, bias, bias stability, scale factor error and stability, random walk, input axis misalignment, limited bandwidth and output resolution. The IMU model runs at a continuous rate and reads in the truth input data continuously. However, the outputs are sampled at discrete times.

2.4.3. Sun Sensor

In principle the Sun sensor model reflects an analogue Sun sensor. The sensor measures the intensity of the solar light and produces a voltage. The sensor measurement itself is corrupted by misalignment and noise and some internal sensor dynamics. The Sun sensor model under development for HPS is based on the mission-specific component for the AsteroidFinder/SSB mission [12]. Next to a few adaptations a dedicated test procedure still has to be defined.

2.4.4. Magnetometer

Magnetometers are common sensors on satellite systems [20] as they are reliable and cost efficient sensors that measure the magnetic field vector. Mainly there are two different principles to measure the magnetic field vector. The first one is called Fluxgate. A Fluxgate magnetometer consists of a small, magnetically susceptible, core wrapped by two coils of wire. An alternating electrical current is passed through one coil to drive the core through an alternating cycle of magnetic saturation. This constantly changing field induces an electrical current in the second coil which can be measured by a detector. In a magnetically neutral background both currents (input, output) will match. If the core is exposed to a magnetic field the component along the core induces a current inside the coils. Due to this fact the input and the induced current will be out of step. The step size is depending on the magnetic field strength and can be used to measure the magnetic field.

The second principle uses the anisotropic magneto resistive (AMR) effect. This effect uses the property of ferromagnetic material to change its internal electromagnetic resistor under the influence of an external magnetic field. The resistor value change can be measured and interpreted as a change in the external magnetic field.

Within DLR several magnetometer models exist which cover the different measurement principles. The models were developed for the AsteroidFinder/SSB and the CLAVIS mission, but they did not undergo extensive testing and verification yet. After appropriate testing they will be integrated into the HPS.

2.4.5. Earth Sensor

Another typical sensor for satellites is an Earth sensor. Earth sensors are used to determine the position vector of the Earth with respect to the satellite. They are mainly based on infrared detection and, like Sun sensors, return voltages. Some examples of such sensors can be found in [20]. Earth sensors represent a low-cost alternative to star trackers but have several disadvantages compared to them, e.g. the placement of Earth sensors obviously needs to be on the side of the satellite pointing towards the Earth whereas the star tracker basically can be located anywhere. Demand-based an inclusion of Earth sensor models has not been realized for the HPS library so far.

2.4.6. Magnetic Torquer

Magnetic attitude stabilization and control is one of the oldest principles used on satellites [20]. The basic principle is to produce a magnetic field vector inside the satellite. Due to the interaction of the satellite magnetic field vector with the geomagnetic field vector a torque is produced and the satellites attitude can be controlled. An artificial and controllable magnetic field vector on board of a satellite can be generated by electromagnetic coils. Two different systems exist. One is using an electrical wire that is wound around a frame many times. This type is often referred to as "air coils". The other and more efficient system is using a torque rod. Here the electrical wire is wound around an inner core with a specific permeability. The inner core allows reaching a higher dipole moment without consuming more electrical power as it would be the case for coils without an inner core.

The basic mathematical description of the HPS magnetic torquer model does not rely on its design. It is based on a description inside [20] but was extended to model the transfer function between the commanded and the achieved dipole moment. Typically this transfer function can be described as a PT1 transfer function where only the time constant T1 at which 63% of the commanded dipole moment is reached has to be specified. In addition the saturation dipole moment is set by the user. In order to allow a quite simple usage the single torquers are combined as a triad, to directly setup three orthogonally arranged magnetic torquers.

2.4.7. Reaction Wheel

Reaction wheels (RW) represent another actuator on board of satellites. They exist in many different versions e.g. as momentum wheels (MW), reaction wheels or control momentum gyros (CMG). Basically they are all related to the same principle of conversion of angular momentum.

Every wheel can be described as a symmetrically rotating mass where its rotating axis is connected to the satellite structure. Due to the rotation of the mass the wheel produces a torque when the mass is accelerated about its axis of rotation. While the wheel is rotating it contains an initial constant angular momentum vector. This angular momentum vector can be transferred from the reaction wheels to the satellite and backwards without changing the overall angular momentum. This is the principle of conversion of angular momentum and can directly be used for attitude control.

Currently a detailed reaction wheel model for the AsteroidFinder/SSB mission does exist. A reduced version of this model will be integrated into the HPS.

The mathematical model of a single simple reaction wheel can be realized using

$$T_{\mathrm{rw}} = I_{\mathrm{rw}}\dot{\omega}_{\mathrm{rw}} + \eta_{\mathrm{rw}}(\omega_{\mathrm{rw}}) \tag{2}$$

where T_{rw} is the torque that is acting on the satellite, I_{rw} is the moment of inertia of the wheel around its spinning axis, and $\dot{\omega}_{\mathrm{rw}}$ is the angular acceleration that is commanded to the reaction wheel. The disturbing noise that is included in every reaction wheel can be modeled as a transfer function η_{rw} which is depending on wheel speed and driven by white noise. In addition to the disturbing noise there exists a maximum wheel speed which defines the maximum angular momentum limit of a reaction wheel. These two boundaries are checked inside the model for the angular momentum as well as for the angular rate.

2.4.8. Thruster

Thrusters are another major actuator on board of satellites and spacecrafts. They exchange impulse with their environment. Due to the arrangement with respect to the body fixed frame different control authorities can be achieved. Current thruster models developed at DLR are adapted for HPS and will be integrated after they have passed predefined test procedures.

2.5. Transformations and Mathematics

A set of useful functions and utilities is provided inside the transformation and mathematics libraries. The transformation library is subdivided into date and coordinate transformations. The date sub-library includes conversions and operations between modified Julian and calendar date, decimal date and day of year. The coordinate transformation sub-library covers the conversion between different coordinates, builds transformation matrices and performs some related quaternion algebra. The basic quaternion algebra together with standard mathematical operations can be found in the mathematics library.

3. Simulator Application

Currently the simulator is used inside DLR and ZARM for several projects. The wide range of the projects shows that HPS can support the GNC-Engineers in every design phase. Three selected applications are described in the following sections covering aspects like post-simulation for validation purpose, investigation of dynamic effects on ACS performance and development and testing of ACS components.

3.1. Gravity Probe B

The HPS simulator dynamics is validated extensively through comparison to analytical solutions, reference data, and actual flight data. The recent MiL application to the relativity mission Gravity Probe B has led to a full validation of the multi-body dynamics.

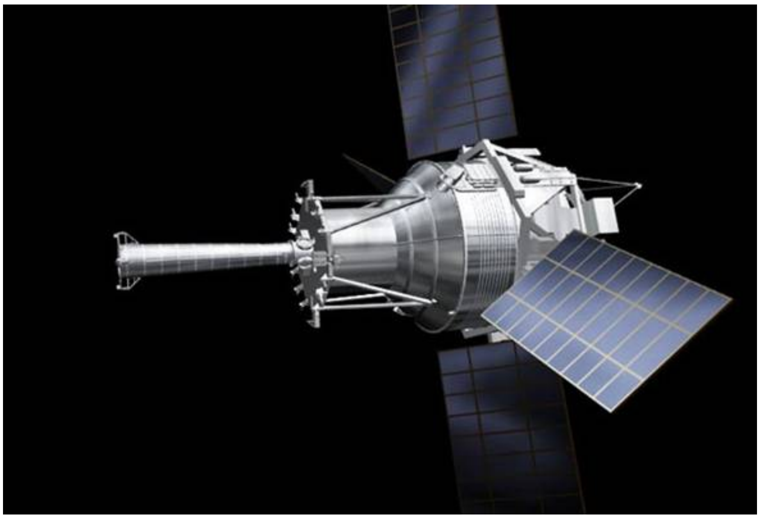

Figure 7. Gravity Probe B spacecraft

Gravity Probe B was developed by NASA and Stanford University and launched in 2004 to test two predictions of Einstein's general theory of relativity. The spacecraft is equipped with a telescope pointing to a distant guide star providing a reference direction, and four precise gyroscopes used for drift rate measurements. Details about the mission can be found in [5]. The coupled multi-body setup of spacecraft and gyroscopes has been investigated in detail post-mission for validation purposes. By comparing the simulated results with actual flight data, a thorough validation of the full model dynamics could be carried out. The end-to-end simulator development and selected simulation results are shown in [16]**.**

3.2. AsteroidFinder/SSB

The AsteroidFinder/SSB mission is a compact satellite project which is build inside DLR. It is scheduled for launch in the middle of 2014. The satellite itself will have a mass of about ~130 kg and its dimensions are ~0.8 x 0.8 x 180 m.

The main payload is a telescope which will take pictures of the sky and identifies near Earth asteroids (NEOs) [10]. The AsteroidFinder telescope is placing challenging requirements towards the attitude control system. These requirements have to be analyzed and simulated precisely. Special care has to be taken for the inertial fine pointing mode and the slewing capabilities of the spacecraft.

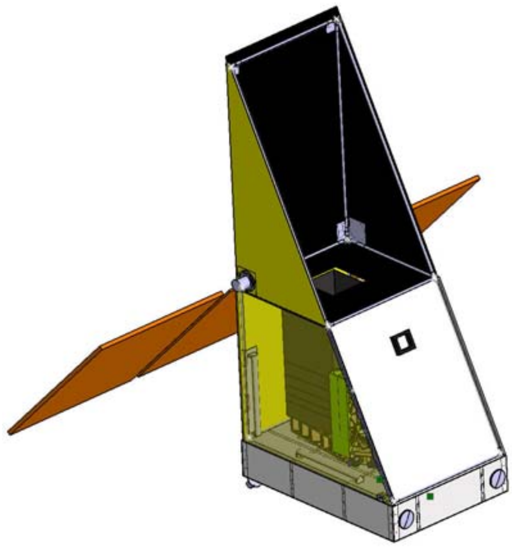

Figure 8. AsteroidFinder/SSB configuration in January 2011

This issue was addressed applying appropriate HPS simulator capabilities; especially the dynamic core is used to model a flexible spacecraft which consists of the main rigid body, the three flexible solar panel segments and the flexible Sun shield, which protects the telescope from direct Sun light.

Due to the fact that AsteroidFinder/SSB uses four reaction wheels to control its attitude these flexible appendages can start to resonate with the reaction wheels and therefore corrupt the image which is taken by the telescope. To analyze this interconnection a mission simulator is developed to allow a very early estimation and characterization of low mode flexibility effects on the telescope images.

3.3. CLAVIS

Another satellite system for which HPS is used is the CLAVIS bus [18]. CLAVIS is a nano satellite (see Fig. 9) with a mass of approximately 10 kg, which is used as technology demonstrator inside DLR. The first payload of the CLAVIS satellite bus will be AISat, which will detect the AIS

(Alarm Indication Signal) signal of ships from space. AISat mainly represents a radio receiver with a four meter helix antenna.

The attitude control is based on three orthogonally arranged magnetic torquers in connection with a magnetometer and three rate gyros. Due to the large helix antenna the gravity gradient force will be used for stabilization as well. For the development and testing of the ACS several models of the HPS are used.

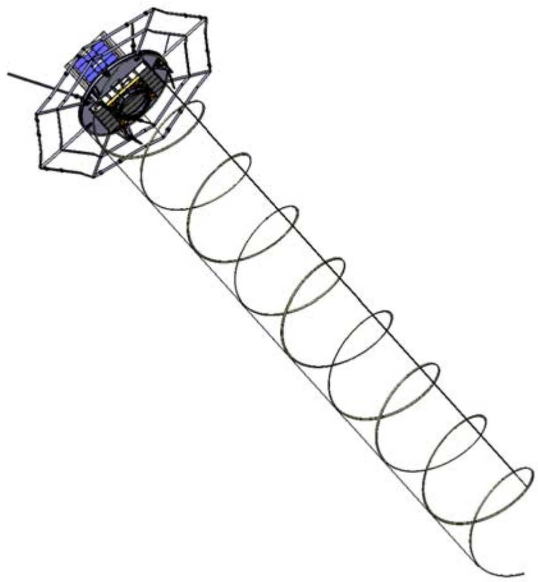

Figure 9. CLAVIS satellite bus with AISat payload in January 2011

Currently a hardware-in-the-loop environment is setup. Therefore an engineering model of the onboard computer [9] is placed into a set of Helmholtz coils (see Fig. 10). On the onboard computer board a magnetometer [13] is mounted and three pulse with modulation (PWM) signals can be generated which are used to drive the magnetic torquers.

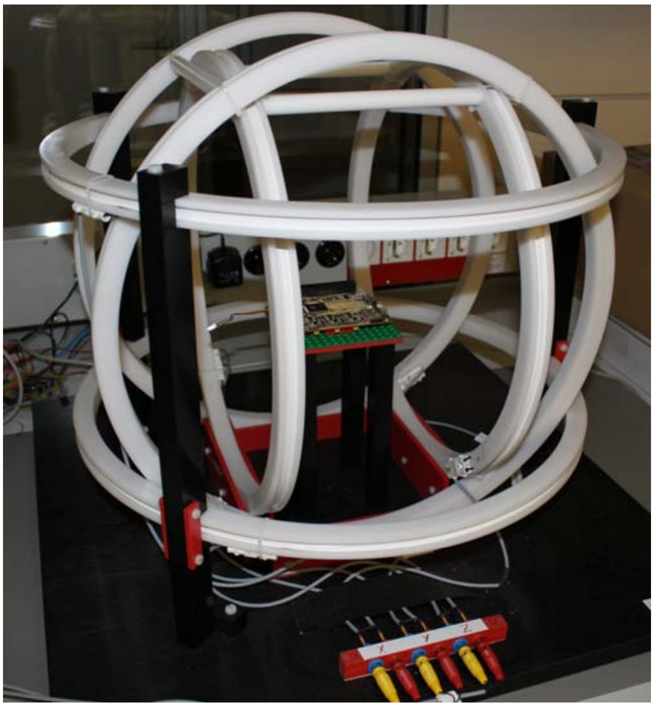

Figure 10. Helmholtz coils testbed for the magnetic attitude control of the Clavis satellite bus.

The external Helmholtz coils and the PWM outputs of the onboard computer are connected to a dSpace real time system. The dSpace system is simulating the satellite dynamics and the space environment and controls the Helmholtz coils, while the real attitude control software is executed on board of the spacecraft computer. For the dynamic and space environment simulation on the dSpace side the HPS models are used (the simulator is shown in Fig. 11). This setup allows fully verifying the real attitude control software on the real hardware, which will be used in space. In a first step, part of the hardware, i.e. the rate gyros and the magnetic torques are simulated on the dSpace system as well.

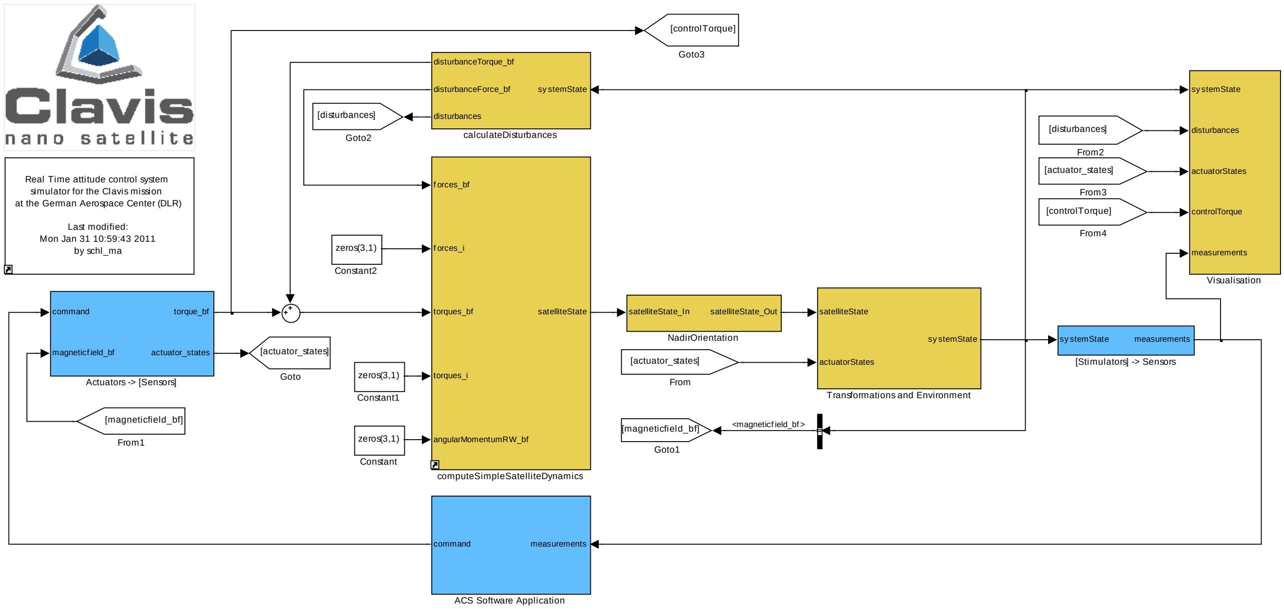

Figure 11. Matlab/Simulink attitude control systems simulator for the Clavis satellite bus

4. Summary and Conclusions

In an effort to establish a re-usable, reliable, and versatile tool for spacecraft dynamics and control simulation, a software library is being developed covering a wide range of aspects between pre-processing, sub-system investigation, end-to-end simulation and post-processing. The library is constantly updated and enhanced by new models and tools as new models or satellite data become available. A major focus is laid upon model adaptation for application with hardware-in-the-loop testing. In order to increase fidelity, a quality assurance process has been established insuring that only properly documented and validated models become part of the library. Next to comprehensive verification, the frequent usage of the simulator for different missions and purpose also contributes to model improvements not only with respect to accuracy but also efficiency. The sample of applications that has been presented gives an insight towards the versatility of the simulator and the effort taken to ensure that modeled dynamics reflect reality also for coupled systems with high performance requirements and increasing complexity.

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