A Modelica Library for Space Flight Dynamics

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Abstract

The Modelica Space Flight Dynamics Library has been developed as a unified environment to be used throughout the design cycle of the Attitude and Orbit Control System (AOCS) for a generic multibody, possibly flexible, spacecraft. The library architecture has been recently redesigned, exploiting at its best Modelica's reusability, flexibility and modularity features. In this contribution the main benefits of the Space Flight Dynamics Library are discussed with special emphasis posed upon flexibility and advantage of exploiting Modelica's nonlinear dynamic inversion capability for preliminary assessment of disturbance torques in nominal orbit and attitude.

Keywords: space flight dynamics; replaceable model; flexibility; simulation

1 Introduction

There is an increasing need for efficient design tools in every domain involved in spacecraft design, and particularly in the area of control oriented modelling and simulation. Specific tools have to be developed for the design of both the system architecture and the Attitude and Orbit Control System (AOCS), bearing in mind the principles of reusability, flexibility and modularity. The main issue in the development of such tools should be to try and work out a unified environment to be used throughout the design cycle of the AOCS, namely, the mission analysis stage, the preliminary and detailed design and simulation phases, the generation and testing of the on-board code, the development of the AOCS Electrical Ground Support Equipment (EGSE) and the post-launch data analysis activities. A number of commercial tools are available to support one or more of the above mentioned phases in the development of AOCS subsystems, however none of them seems capable of providing complete coverage of the whole development cycle in a sufficiently flexible way. Moreover, the spacecraft architecture is traditionally designed using domain specific software packages that best solve their tasks with respect to the different disciplines involved, e.g., flight mechanics, propulsion, controls; as a drawback, it is quite cumbersome to link together the different model components and exploit their reusability in the framework of future missions.

The Modelica Space Flight Dynamics Library provides a systematic approach to simulation of spacecraft dynamics based on modern acausal object-oriented modelling techniques. The development of simulation tools for satellite attitude and orbit dynamics within the object-oriented paradigm has been the subject of previous work (see [14], where an overview of the existing tools for AOCS modeling is presented). Surprisingly enough, however, while the use of Modelica for aerospace applications has led to the development of a library for flight dynamics (see [8]), very little activity in the spacecraft domain has been reported. Some preliminary results in the development of a Modelica spacecraft modeling library have been presented in [4, 11, 5]). More recently, the model components presented in the cited references have been revised in order to take advantage of the Modelica MultiBody library (see [9]) which turns out to be extremely suitable to serve as a basis for the development of the basic model components for the mechanical parts of spacecraft models. In particular, a recent extension of the above mentioned library (see [2, 13]) is proving specially beneficial for the simulation of spacecraft with flexible appendages (see [12]).

In this paper the new Space Flight Dynamics Library is described, emphasizing its flexibility and showing the advantage of exploiting Modelica's nonlinear dynamic inversion capability for the preliminary assessment of disturbance torques acting upon a spacecraft in nominal orbit and attitude. The paper is organized as follows: first the Space Flight Dynamics Library will be described in detail in Sections 2-3; subsequently, the library flexibility will be exploited in Section 4 in a preliminary analysis of the external disturbance torques acting on a spacecraft in its nominal orbit and attitude. Finally, in Section 5 concluding remarks will be outlined.

2 The Space Flight Dynamics Library

Modelica turns out to be specially suited for the modelling of spacecraft dynamics under many respects:

- Coordinate frames can be simply included in the model in terms of connectors, describing kinematic transformations from one coordinate system to another.
- Spacecraft dynamics can be modelled by extending suitable classes available in the MultiBody Library.
- Specific Modelica constructs are available to deal with the modelling of physical fields and environmental quantities. This feature turns out to be extremely useful in modelling the space environment and representing the interaction between the environment and the spacecraft. In particular, with a suitable choice of the environment interfaces, models of increasing complexity for each of the relevant environmental fields can be implemented.
- Sensors and actuators can also be easily represented in the Modelica paradigm. For instance, a component for the simulation of magnetic torquers is modelled in terms of the interaction with the geomagnetic field, while the momentum exchange between spacecraft and wheels is modelled via a simple mechanical connector allowing one rotational degree of freedom [1].
- Packages of data sheets for each class can be constructed and components easily modified within each spacecraft model, using Modelica's advanced features (see, e.g., [10]).
- *C code* can be easily linked to Modelica models, allowing the designer to reuse, for instance, a wide range of available specific algorithms and routines he is confident with, without going through all the trouble of re-implementing them in Modelica code.
- Finally, as the components of the library are independent from each other, one can exploit this flexibility in order to build a simulation model of increasing complexity and accuracy according to the needs associated with each phase of the AOCS development process.

In addition, the availability of the Modelica MultiBody Library (see [9]) leads to further advantages, since the MultiBody components can be extensively reused. Furthermore, recent developments to the library allowing the modeling and simulation of flexible multibody systems (see [2, 13]) make it possible to deal with the dynamics of spacecraft with flexible appendages such as gravity gradient booms, antennas or solar panel arrays.

The Space Flight Dynamics Library encompasses all necessary utilities to ready a reliable and quick-to-use scenario for a generic space mission, providing a wide choice of most commonly used models for AOCS sensors, actuators and controls. The Space Flight Dynamics Library's model reusability is such that, as new missions are conceived, the library can be used as a base upon which readily and easily build a simulator. This goal can be achieved simply by interconnecting the standard Space Flight Dynamics Library objects, possibly with new components purposely designed to cope with specific mission requirements, regardless of space mission scenario in terms of either mission environment (e.g., planet Earth, Mars, solar system), spacecraft configuration or embarked on board systems (e.g., sensors, actuators, controls).

Section 3 deals with a thorough description of the main Space Flight Dynamics Library components.

3 Basic model components

The generic spacecraft simulator will consist of an extended **World** model and one or more **Spacecraft** models:

1. Extended **World** model: a new **World** model, extending **Modelica.MultiBody.World** has been defined. It provides all the functions needed for a complete representation of the space environment as seen by an Earth orbiting spacecraft:
    - Gravitational field models;
    - Geomagnetic field models;
    - Atmospheric models;
    - Solar radiation and eclipse models;

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[1] Mounting errors, which may give rise to inter-axis coupling and vibrations, can be easily accounted for.

- Models for Sun and Moon ephemeris;

Such an extension to the basic **World** model as originally provided in the MultiBody library plays a major role in the realistic simulation of the dynamics of a spacecraft as the linear and angular motion of a satellite are significantly influenced by its interaction with the space environment.

2. **Spacecraft** model: a completely reconfigurable spacecraft including components:
    (a) **SpacecraftDynamics**: this component has been defined by extending the rigid body model on the basis of the already available **Modelica.MultiBody.Parts.Body** component. The main modifications reside in the selectable evaluation of the interactions between the spacecraft and the space environment and on the additional initialization option for the simulation via selection of a specific orbit for the spacecraft. Data for custom orbits and spacecraft inertial properties and geometry (influencing both aerodynamic and solar radiation behavior) are stored in dedicated library packages. The **SpacecraftDynamics** interface consists of the standard Modelica library mechanical connector.

    (b) **SensorBlock**: this *replaceable* model consists in a reconfigurable set of attitude sensors to be chosen among custom Space Flight Dynamics Library **SensorBlock** implementations. The model *replaceable* feature is active on all levels, such that, for instance, the same basic **Spacecraft** model can be instantiated as having a custom star tracker sensor (corresponding to a specified supplier's serial number), model (such as ideal measure, measure corrupted by simple white noise and bias, optional time delay and availability bit) and configuration (defined by star trackers number, location and orientation with respect to the spacecraft's reference frame).

    The Space Flight Dynamics Library encompasses mathematical models of different degree of complexity for star sensors, gyroscopes, magnetometers and GPS receivers. The **SensorBlock** interface consists of a standard Modelica library mechanical connector toward model **SpacecraftDynamics** and of the expandable connector (see [1]) **SensorBus** toward replaceable model **ControlBlock**.

    (c) **ActuatorBlock**: this *replaceable* model consists in a reconfigurable set of attitude control actuators to be chosen among custom Space Flight Dynamics Library **ActuatorBlock** implementations. Mathematical models of different degree of complexity for commonly employed actuators and actuators set have been implemented in the Space Flight Dynamics Library, including momentum and reaction wheels, magnetic torquers and cold gas thrusters. The **ActuatorBlock** interface consists of a standard Modelica library mechanical connector toward model **SpacecraftDynamics** and of the expandable connector **ActuatorBus** toward replaceable model **ControlBlock**.

    Note, in passing, that sensor and actuator models have been developed in a control-oriented framework, i.e., at the current level of refinement they are not based on physical models of the measurement process. More advanced models can however be included in the considered framework if needed.

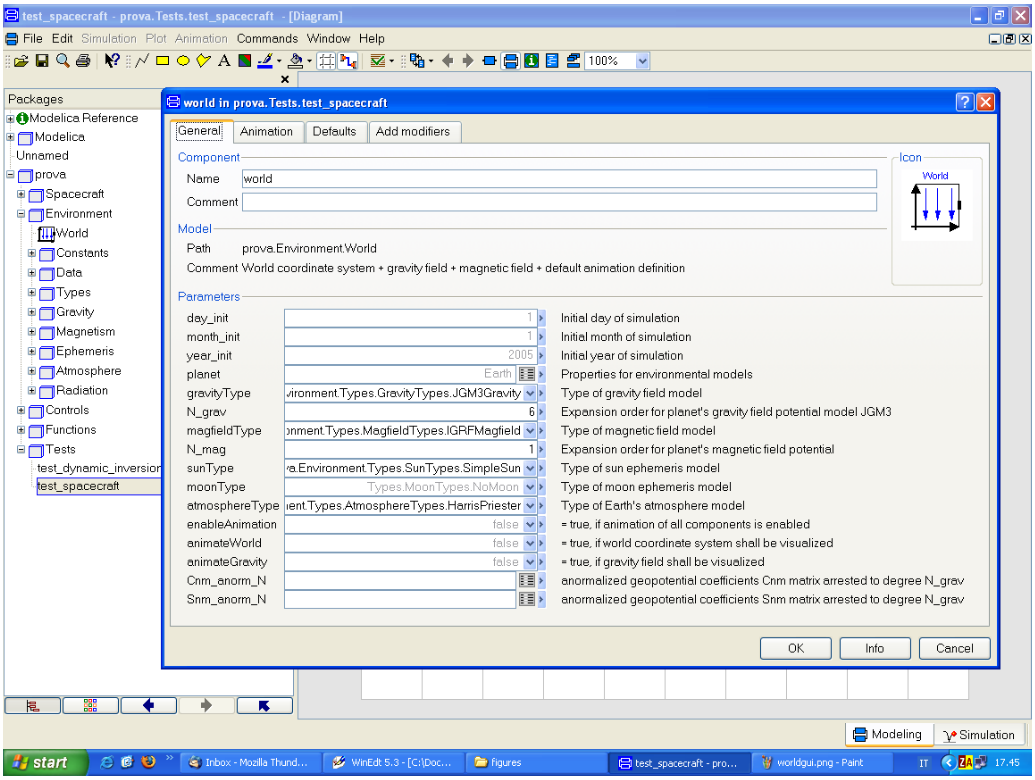
    (d) **ControlBlock**: this *replaceable* model implements the spacecraft Attitude Control System (ACS), including blocks supervising the basic attitude determination, attitude control and control allocation functions. The **ControlBlock** interface consists of two expandable connectors, **SensorBus** and **ActatorBus**, toward replaceable models **SensorBlock** and **ActuatorBlock** respectively.

    Note that the spacecraft can be either modeled as a rigid body or as a multibody system, possibly with flexible appendages (see [12] for details).

A short description of the Space Flight Dynamics Library's **World**, **Spacecraft** and **SpacecraftDynamics** models is given in the following subsections; **SensorBlock**, **ActuatorBlock** and **ControlBlock** models are omitted for brevity.

3.1 Extended World model

The user interface for Extended World Model component is shown in Figure 1; as can be seen from the Figure, the user can define the initial date and time of



Component

Name: world

Comment:

Model

Path: prova.Environment.World

Comment: World coordinate system + gravity field + magnetic field + default animation definition

Parameters

day_init	1	Initial day of simulation
month_init	1	Initial month of simulation
year_init	2005	Initial year of simulation
planet	Earth	Properties for environmental models
gravityType	vironment.Types.GravityTypes.JGM3Gravity	Type of gravity field model
N_grav	6	Expansion order for planet's gravity field potential model JGM3
magfieldType	onment.Types.MagfieldTypes.IGRFMagfield	Type of magnetic field model
N_mag	1	Expansion order for planet's magnetic field potential
sunType	va.Environment.Types.SunTypes.SimpleSun	Type of sun ephemeris model
moonType	Types.MoonTypes.NoMoon	Type of moon ephemeris model
atmosphereType	ient.Types.AtmosphereTypes.HarrisPriester	Type of Earth's atmosphere model
enableAnimation	false	= true, if animation of all components is enabled
animateWorld	false	= true, if world coordinate system shall be visualized
animateGravity	false	= true, if gravity field shall be visualized
Cnm_anorm_N		anormalized geopotential coefficients Cnm matrix arrested to degree N_grav
Snm_anorm_N		anormalized geopotential coefficients Snm matrix arrested to degree N_grav

Figure 1: User interface for the Extended World model.

the simulation and choose among the available models for the Earth's gravity field (J_2, J_4 or the more general *JGM*-3 model for the Earth's gravitational potential, see [7]), for the Earth's magnetic field (dipole, quadrupole and the IGRF model, see [16]), for the atmospheric density model and for the Sun and Moon ephemeris tables.
As is well known, the Earth's gravitational potential U_g may be described by the function

$$U_g(r,\theta,\lambda) = -\frac{\mu}{r}\{1+\sum_{n=2}^{\infty}(\frac{R_e}{r})^n J_n P_n(cos(\theta))+$$

$$+\sum_{n=2}^{\infty}\sum_{m=1}^{n}(\frac{R_e}{r})^n P_n^m(cos(\theta))(C_n^m cos(m\lambda)+S_n^m sin(m\lambda))\}$$

where P_n^m are the Legendre polynomials

$$P_n(x) = \frac{1}{2^n n!}\frac{d^n}{dx^n}(x^2-1)^n$$

$$P_n^m(x) = (1-x^2)^{m/2}\frac{d^m P_n(x)}{dx^m}$$

R_e is the mean equatorial Earth radius, r,θ and λ are the point's spherical coordinates and coefficients J_n, C_n^m, S_n^m are the zonal, sectoral and tesseral coefficients. Depending on the mission characteristics and on the purpose of attitude control simulations, a satisfactory approximation can be obtained by choosing the order of the expansion in a suitable way. The Earth gravitational field components (expressed in spherical coordinates) are then given by

$$g = -\nabla U_g = -\{\frac{\partial U_g}{\partial r}, \frac{1}{r}\frac{\partial U_g}{\partial \theta}, \frac{1}{r\,sin(\theta)}\frac{\partial U_g}{\partial \lambda}\}.$$

Similarly, the geomagnetic potential U_m, is described by the function

$$U_m(r,\theta,\lambda) = \frac{R_e}{\mu}\sum_{n=0}^{\infty}\sum_{m=0}^{n}(\frac{R_e}{r})^{n+1}P_{nm}(cos(\theta))$$

$$(g_n^m cos(m\lambda)+h_n^m sin(m\lambda))$$

where g_n^m and h_n^m are the Gauss coefficients appropriate to the Schmidt polynomials P_{nm}

$$P_{n,0}(x) = P_n^0(x)$$

$$P_{n,m}(x) = (\frac{2(n-m)!}{(n+m)!})^{1/2}P_n^m(x).$$

The coefficients for the geomagnetic potential adopted in the simulation environment correspond to the so-called International Geomagnetic Reference Field (IGRF) model for the Earth's magnetic field (see [16]). The components of the geomagnetic field (expressed in spherical coordinates) are then given by

$$B = -\nabla U_m = -\{\frac{\partial U_m}{\partial r}, \frac{1}{r}\frac{\partial U_m}{\partial \theta}, \frac{1}{r\,sin(\theta)}\frac{\partial U_m}{\partial \lambda}\}.$$

Similar models for the atmospheric density and the Sun and Moon position have been implemented, according to [7, 15].

3.2 Spacecraft model

The **Spacecraft** model is structured according to the diagram in Figure 2: the component associated with the (perturbed) linear and angular dynamics of the satellite (described in Figure 3) is connected to the actuators and sensors blocks via a standard Modelica mechanical connector, whilst the interconnection among sensors, actuators and control blocks is realized via suitably defined data buses. For instance, the default choice for the replaceable model **SensorBlock**, comprising a single star tracker, gyroscope, GPS receiver and magnetometer, is depicted in Figure 4. As can be seen from the Figure, models for each of the on-board sensors are included; in particular, each sensor is characterized by a mechanical interface, corresponding to the physical mounting of the instrument on the satellite body (taking into account the definition of the local sensor reference frame via a suitable change of coordinates) and by a signal interface. The sensors data bus is therefore defined by the collection of output signals coming from each of the available sensors (using Modelica expandable connectors, see [1]).

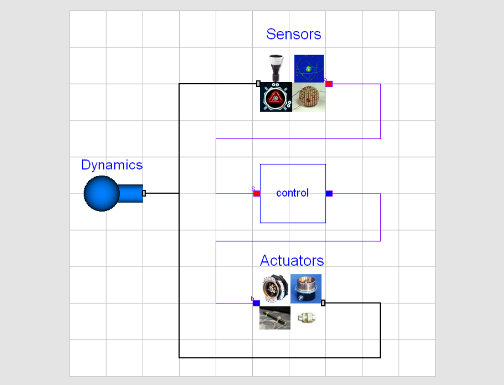


Figure 2: Structure of the Spacecraft model.

Note that the sensor and actuator models have been defined by taking full advantage of the object orientation of the modeling language: the core definition for each sensor/actuator model is at the interface level; mathematical models of increasing complexity are available, ranging from ideal sensors providing ideal, continuous-time measurements to more refined models taking into account measurement errors and the actual sampling rate of the sensors.

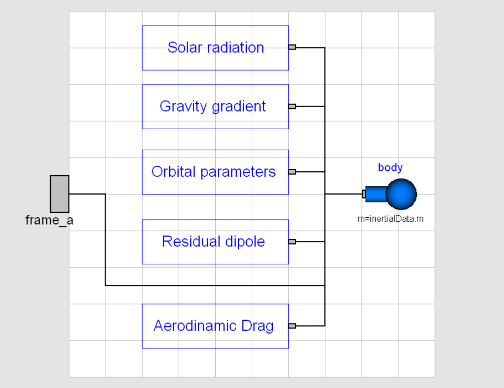


Figure 3: Layout of the SpacecraftDynamics model.

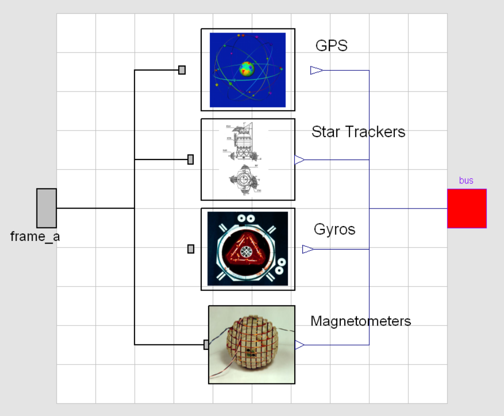


Figure 4: Default choice for replaceable model **SensorBlock**, comprising a single star tracker, gyroscope, GPS receiver and magnetometer.

Let us stress the point that the Space Flight Dynamics Library **Spacecraft** model is completely customizable for what concerns actuators, sensors and controls, which can be selected among standard library models via dedicated popup menus from the model **Spacecraft** graphical user interface (see Figure 5). The possible customization are virtually countless: Limiting the discussion only to possible sensors customization, the present Space Flight Dynamics Library implementations allows for choosing among all possible combinations arising from:

- 3 star tracker models ;
- 2 star tracker configurations ;
- 2 GPS models;
- 1 magnetometers models;

- 2 gyroscope models;
- 4 sensors block instances.

Figure 6 provides an idea of the customization made possible by the Space Flight Dynamics Library for what attains the **SensorBlock** only.

More freedom yet is available within the **Spacecraft-Dynamics** model for what attains the interaction of the spacecraft with the space environment as defined in the extended **World** model, via the options for activation/deactivation of magnetic residual dipole, aerodynamic and solar radiation disturbance forces and torques.

The **Spacecraft** model extreme flexibility was achieved by setting Dymola provided annotation option **choicesAllMatching** to true for all the replaceable models. In such a way, a model is a candidate for redeclaration of a given replaceable model if and only if it extends a suitable base interface **thisModelFamily-Interface**. If a new model candidate is designed, **Dymola** will automatically update the candidate model list with the new entry, provided it is an extension of the proper interface. Finally, the **choicesAllMatching** annotation adoption prevents the user from unsuitable redeclarations.

3.3 SpacecraftDynamics model

This new component uses the Modelica.MultiBody.Parts.Body model to account for the interaction between the spacecraft and the environment. In particular, the following disturbance forces and torques can be selectively included in the spacecraft model:

- Gravity gradient torques;
- Magnetic torques, arising from the presence of a non zero spacecraft's residual magnetic dipole;
- Aerodynamic forces and torques, produced by the interaction with the planet's atmosphere;
- Solar radiation pressure originated disturbance forces and torques.

Specifically, the latter contributions to the disturbance forces and torques requires the definition of the interaction between the spacecraft geometry, defined as an assembly of planar and possibly cylindrical surfaces, and the average solar radiation pressure Φ. When the spacecraft is fully illuminated, the force acting upon a single exposed surface is given by the momentum exchange law

$$\frac{d\,q_{sc}}{dt} = p_{\odot}\frac{(1AU)^2}{\|R\|^2}\sum_{i=1}^{\#surf} A_i\,cos(\theta_i)\cdot \\ [(1-\varepsilon_i)(-\hat{R}) + 2\varepsilon_i\,cos(\theta_i)(-n_{ext,i})]$$

where q_{sc} is the spacecraft's momentum, $p_{\odot} = 4.56e^{-6}Jm^{-2}$ is the mean solar radiation pressure at 1 Astronomic Unit (AU), R is the relative position vector from the spacecraft center of mass to the Sun, A_i, ε_i and $n_{ext,i}$ are the single surface area, reflectivity coefficient and external surface unit vector, respectively. Finally, $\theta_i = acos(\hat{R}\cdot n_{ext,i})$.

When a body interposes between the spacecraft and the Sun, the former is partially or totally eclipsed, and the force reduces accordingly by a factor[2]

$$\nu(r_{sun}, r_{s/c}) = 1 - \left(\frac{\alpha a^2 + \beta b^2 - ac\,sin\alpha}{\pi b^2}\right)$$

where

$$\alpha = arcsin\left(\frac{b\,sin\beta}{a}\right), \quad \beta = arccos\left(\frac{c^2 + b^2 - a^2}{2bc}\right)$$

a, b are the Sun and occulting body apparent radii respectively, and c is the apparent distance between the geometrical centers of Sun and occulting body.

Thus, the overall force acting on the spacecraft is

$$\frac{d\,q_{sc}}{dt} = \nu \cdot p_{\odot}\frac{(1AU)^2}{\|R\|^2}\sum_{i=1}^{\#surf} A_i\,cos(\theta_i)\cdot \\ [(1-\varepsilon_i)(-\hat{R}) + 2\varepsilon_i\,cos(\theta_i)(-n_{ext,i})]$$

while the associated torque is computed accordingly, once the center of pressure of each and every surface composing the spacecraft geometry is defined.

The layout of the **SpacecraftDynamics** model is depicted in Figure 3. As can be seen from the Figure, the core of the component is the Body component of the Modelica MultiBody library, which describes the linear and angular motion of a rigid body. The component interface is constituted by a mechanical connector, to which mathematical models for the forces and torques arising from the interaction with the space environment are attached. Finally, a function for the computation of classical orbit parameters from the cartesian representation of the spacecraft position and velocity is included in the component model.

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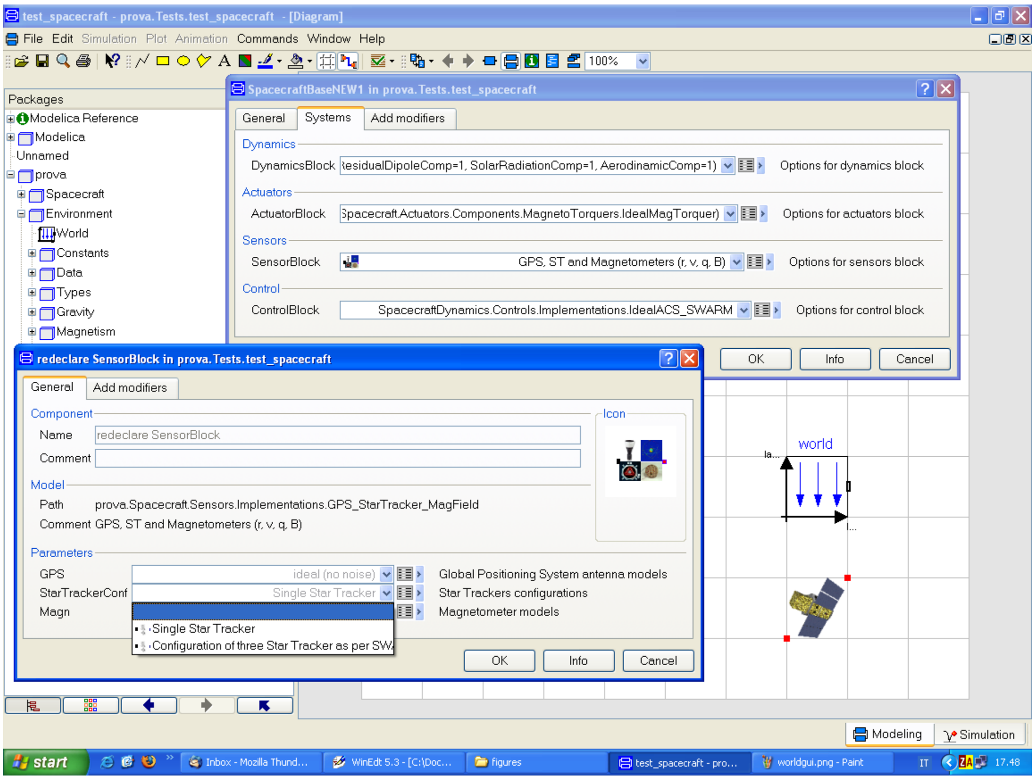
[2] The shadow function $\nu(r_{sun}, r_{s/c})$ is derived under the assumption of occulting body infinitely far from the spacecraft



SpacecraftBaseNEW1 in prova.Tests.test_spacecraft

General | Systems | Add modifiers

Dynamics
DynamicsBlock ResidualDipoleComp=1, SolarRadiationComp=1, AerodinamicComp=1) Options for dynamics block

Actuators
ActuatorBlock Spacecraft.Actuators.Components.MagnetoTorquers.IdealMagTorquer) Options for actuators block

Sensors
SensorBlock GPS, ST and Magnetometers (r, v, q, B) Options for sensors block

Control
ControlBlock SpacecraftDynamics.Controls.Implementations.IdealACS_SWARM Options for control block

OK | Info | Cancel

redeclare SensorBlock in prova.Tests.test_spacecraft

General | Add modifiers

Component
Name redeclare SensorBlock
Comment

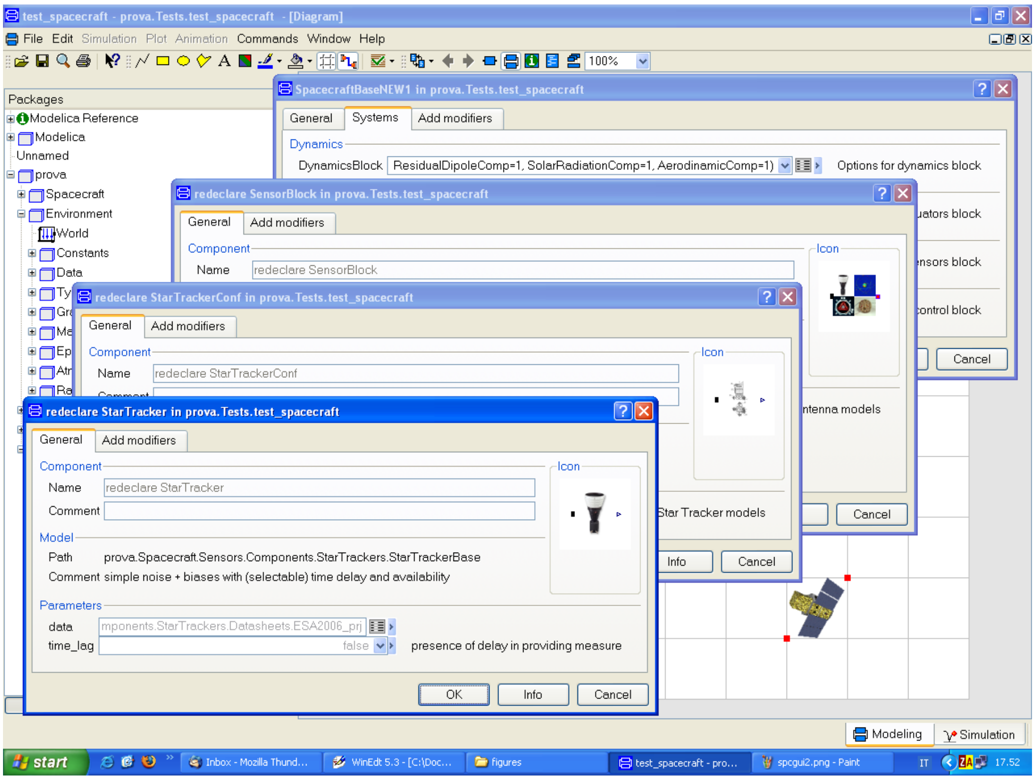
Model
Path prova.Spacecraft.Sensors.Implementations.GPS_StarTracker_MagField
Comment GPS, ST and Magnetometers (r, v, q, B)

Parameters
GPS ideal (no noise) Global Positioning System antenna models
StarTrackerConf Single Star Tracker Star Trackers configurations
Magn Magnetometer models

- Single Star Tracker
- Configuration of three Star Tracker as per SW

OK | Info | Cancel

Figure 5: **Spacecraft** graphical user interface.



SpacecraftBaseNEW1 in prova.Tests.test_spacecraft

General | Systems | Add modifiers

Dynamics
DynamicsBlock ResidualDipoleComp=1, SolarRadiationComp=1, AerodinamicComp=1) Options for dynamics block

redeclare SensorBlock in prova.Tests.test_spacecraft

Component
Name redeclare SensorBlock

redeclare StarTrackerConf in prova.Tests.test_spacecraft

Component
Name redeclare StarTrackerConf

redeclare StarTracker in prova.Tests.test_spacecraft

General | Add modifiers

Component
Name redeclare StarTracker
Comment

Model
Path prova.Spacecraft.Sensors.Components.StarTrackers.StarTrackerBase
Comment simple noise + biases with (selectable) time delay and availability

Parameters
data mponents.StarTrackers.Datasheets.ESA2006_prj
time_lag false presence of delay in providing measure

OK | Info | Cancel

Figure 6: Selection of star tracker instance for **SensorBlock** replaceable model.

The spacecraft data (i.e., inertial properties, geometry, surface reflectivity, material, etc.) can be easily retrieved from appropriate spacecraft records. Moreover, to cope with classic space mission requirements, two initialization options are allowed:

- standard Modelica.Mechanics.MultiBody.Body initialization;
- a new initialization based on current simulation Universal Time (set within the extended World model), nominal orbit (specified by six orbital parameters, retrieved from appropriate records), angular rate and Modelica Orientation object relative to the orbital reference frame.

4 A case study

The Spacecraft Dynamics Library has been already used in a number of spacecraft modelling and simulation problems (see, e.g., [6] and the references therein). In this paper, the focus will be on the application of the library in the AOCS preliminary design stage, i.e., when the spacecraft architecture is not yet completely defined and different options are being evaluated, depending on the specific mission profile. At this stage, it is indeed convenient to maintain for the spacecraft a *higher level* structure (i.e., one where only requirements are specified, not specific equipments), to evaluate its interaction with the space environment for different mission profiles and to be concerned only afterwards about the choice of specific equipment to be embarked. One of the main tasks in this stage is to evaluate the external disturbance forces and torques acting on the spacecraft, depending on the mission profile. This task can be performed in many different ways: the simplest approach would be to rely on simple worst case formulas such as the ones given in [3]; on the other hand, one could think of running a closed-loop simulation using a simple attitude control algorithm to maintain the satellite near its nominal operating conditions (e.g., Earth pointing attitude). Clearly, the former approach will introduce a significant conservatism in the analysis, while the latter requires a preliminary design of the attitude control law, which may be time-consuming.

A better way of dealing with this task can be devised by taking advantage of the acausal nature of Modelica models: Dymola's symbolic dynamic inversion capability will be exploited for the preliminary assessment of the disturbance torques acting upon the spacecraft in its nominal orbit and attitude. Taking advantage of the Space Flight Dynamics Library features, it is an easy task to derive a customization of the base **Spacecraft** model which can be used to perform this preliminary analysis: it is sufficient to *assemble* a new spacecraft model with no **ControlBlock** nor **ActuatorBlock**, to define an unknown *control torque* to be applied as input torque to the spacecraft and assign the desired spacecraft's angular rate time-history. Dymola will then take care of solving the resulting system of nonlinear equations to derive the control torques time history necessary to keep the spacecraft in its nominal attitude.

As an example, Figure 7 shows the computed disturbance torques experienced by an Earth-pointing satellite aligned with its orbital reference frame. The considered satellite is assumed to operate on a near polar orbit ($i = 86.9^\circ$ inclination), eccentricity $e = 0$, altitude of 450 Km and a corresponding orbital period of 5614.8 seconds. The satellite inertial properties are:

- Satellite mass $m = 500\ kg$
- Satellite inertia matrix $[kgm^2]$

$$I = \begin{bmatrix} 30 & 2 & -18 \\ 2 & 1080 & -0.1 \\ -18 & -0.1 & 1070 \end{bmatrix}$$

A default cubic geometry was assumed for the satellite, comprising six surfaces, each with $1\,m^2$ surface area, reflectivity coefficient $\varepsilon = 0.02$ and center of pressure located at the surface geometric center.

For simulation purpose, aerodynamic drag, solar radiation pressure and a residual magnetic dipole of $1\,A\,m^2$ upon each spacecraft's body axis were selected as disturbance torques, while default choices were selected for geomagnetic and gravity fields (i.e., magnetic dipole and J_2 respectively), Sun ephemeris and atmosphere model (i.e., Harris-Priester). The simulation was initialized at GMT 12 : 00, March 21, 2007.

Note that the solar radiation disturbance torque experiences a sudden drop to zero when the Earth interposes between the spacecraft and the Sun, and takes back a nonzero value as soon as the spacecraft gets full Sun illumination.

5 Concluding remarks

In this paper the main issues related to the modelling and simulation of spacecraft dynamics have been described, the results obtained so far in developing Modelica tools for spacecraft simulation have been pre-

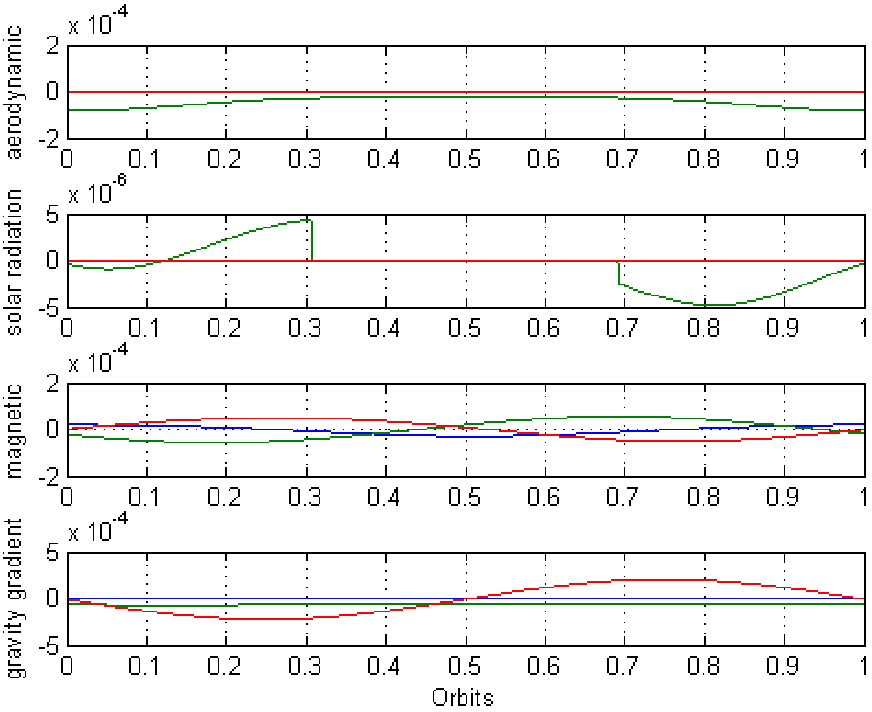


Figure 7: Disturbance torques experienced by the satellite in its nominal orbit and attitude.

sented and a case study demonstrating Modelica's usefulness and flexibility as a design tool has been discussed.

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