Design description of the library for Space Flight Dynamics

Deliverable 7.1

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Abstract

The Modelica Space Flight Dynamics Library is currently under development; its aim is to provide 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. This report describes the library architecture, which will exploit at its best Modelica's reusability, flexibility and modularity features.

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

1 Introduction

The aim of this WP is to exploit existing object-oriented modelling and simulation technologies in order to develop a set of advanced tools for the simulation of spacecraft attitude and orbit dynamics. The goal is to arrive at a detailed, yet easy to use tool which can serve as a reference in the preliminary design and performance assessment of spacecraft attitude and orbit control systems. Particular care shall be placed in the development of the model structure in order to exploit as much as possible the potential advantages of the object-oriented approach.

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 shall provide 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 [8], 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 [4]), very little activity in the spacecraft domain has been reported.

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 when 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 can be modelled in terms of the interaction with the geomagnetic field, while the momentum exchange between spacecraft and wheels can be modelled exploiting the Modelica.Mechanics.Multibody features.
- 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., [6]).
- *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 [5]) leads to further advantages, since the MultiBody components can be extensively reused. Furthermore, recent developments to the library allowing the modelling and simulation of flexible multibody systems (see [2, 7]) 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 shall encompass 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 shall be such that, as new missions are conceived, the library will be used as a base upon which readily and easily build a simulator. This goal shall 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).

3 Basic model components

The generic spacecraft simulator shall 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 shall provide all functions needed for a complete representation of the space environment as seen by an Earth orbiting spacecraft, including:
   - Gravitational field models;
   - Geomagnetic field models;
   - Atmospheric models;
   - Solar radiation and eclipse models;
   - 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, shall include *replaceable* models:

   (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) shall be stored in dedicated library packages. The **SpacecraftDynamics** interface consists of the standard Modelica library mechanical connector.

   (b) **SensorBlock**: it shall consist in a reconfigurable set of attitude sensors to be chosen among custom Space Flight Dynamics Library **SensorBlock** implementations. The model *replaceable* feature shall be active on all levels, such that, for instance, the same basic **Spacecraft** model provide tha capability to 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 shall encompass mathematical models of different degree of complexity for star sensors, gyroscopes, magnetometers, GPS receivers, Sun and horizon sensors. 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**: it shall consist 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 shall be implemented in the Space Flight Dynamics Library, including momentum and reaction wheels, magnetic torquers, cold gas thrusters and control moment gyroscopes. The **ActuatorBlock** interface consists of a standard Modelica library mechanical connector toward model **SpacecraftDynamics** and of the expandable connector **ActuatorBus** toward replaceable model **ControlBlock**.

   (d) **ControlBlock**: it shall implement 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.

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 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 [3]), for the Earth's magnetic field (dipole, quadrupole and the IGRF model, see [10]), 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.

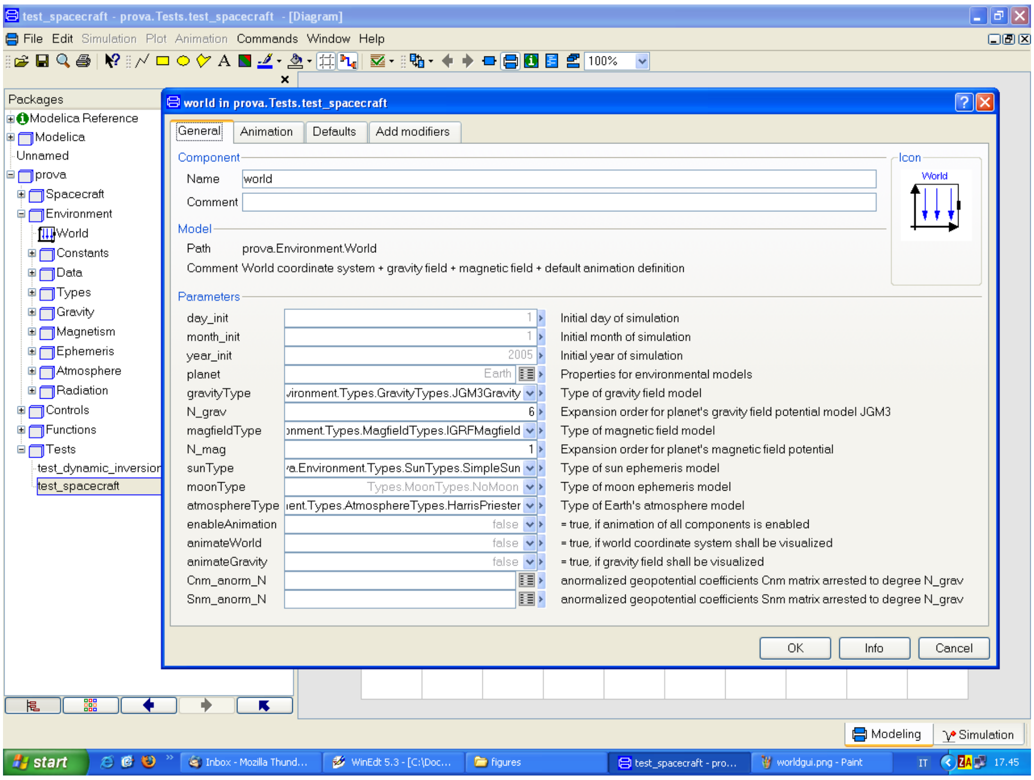

Figure 1: User interface for the Extended World model.

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 [10]). 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 [3, 9].

3.2 Spacecraft model

The **Spacecraft** model shall be 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) shall be connected to the actuators and sensors blocks via a standard Modelica mechanical connector, whilst the interconnection among sensors, actuators and control blocks shall be 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 shall be included; in particular, each sensor shall be 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 shall therefore be defined by the collection of output signals coming from each of the available sensors (using Modelica expandable connectors, see [1]).

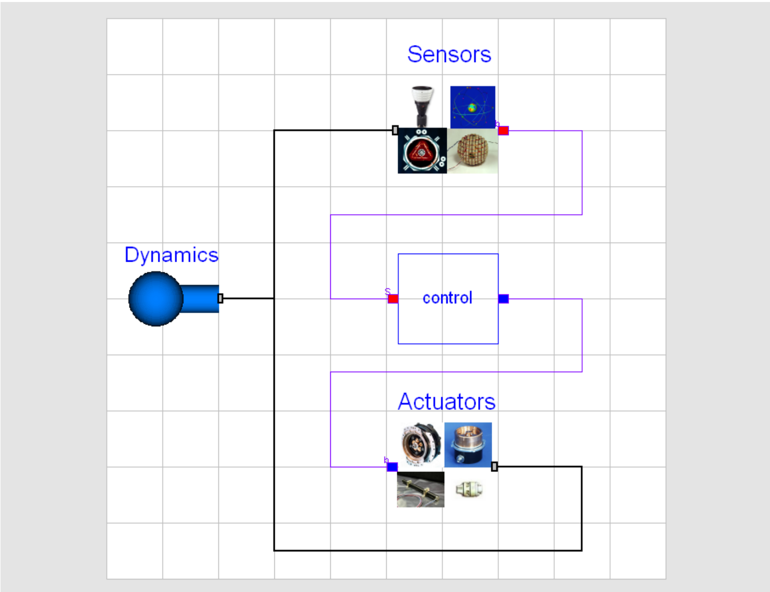

Figure 2: Structure of the Spacecraft model.

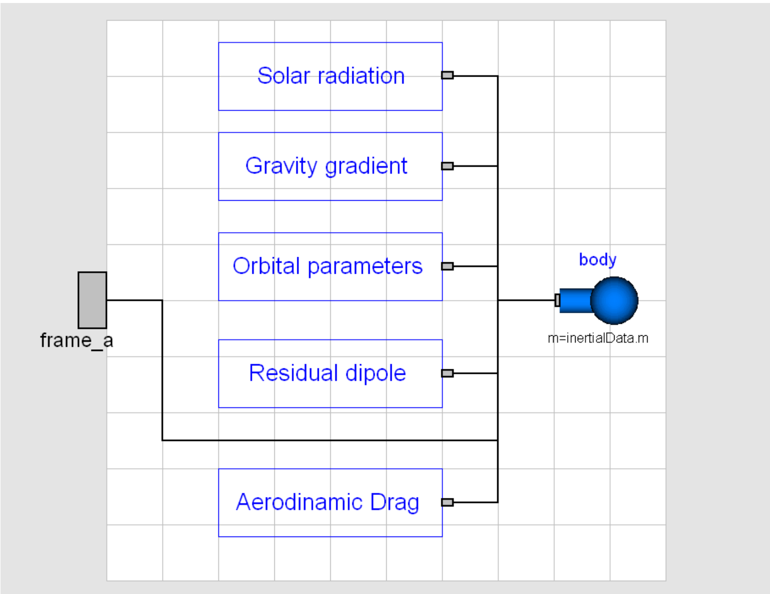

Figure 3: Layout of the SpacecraftDynamics model.

Note that the sensor and actuator models shall be defined by taking full advantage of the object orientation of the modelling language: the core definition for each sensor/actuator model shall be at the interface level; mathematical models of increasing complexity shall be 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.

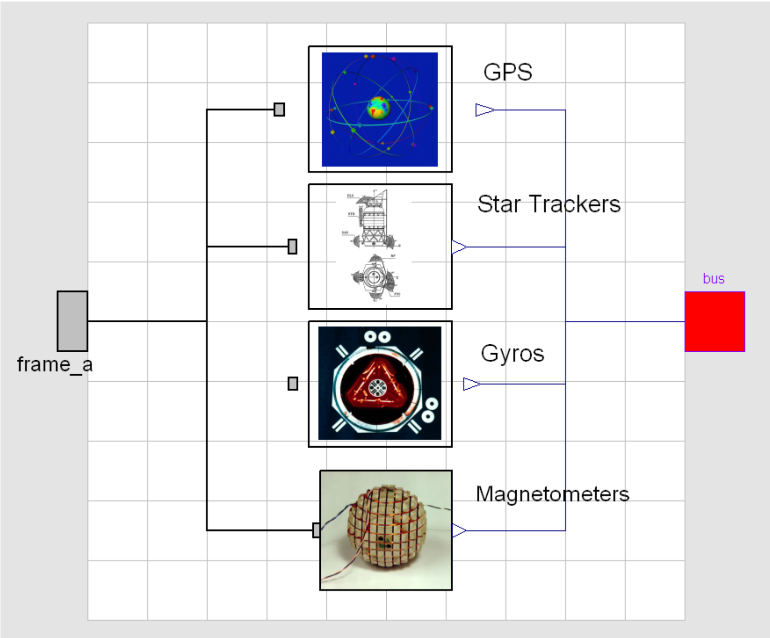

Figure 4: Default choice for replaceable model **SensorBlock**, comprising a single star tracker, gyroscope, GPS receiver and magnetometer.

The Space Flight Dynamics Library **Spacecraft** model shall be completely customizable for what concerns actuators, sensors and controls, which shall be selected among standard library models via dedicated popup menus.

More freedom yet is available within the **SpacecraftDynamics** 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.

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.

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.

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 Concluding remarks

This report provides the design description of the Space Flight Dynamics Library, which is currently under development at DEI, Politecnico di Milano. Up to now, the library encompasses a thorough description of the space environment, including different levels of complexity models for the description of gravity and magnetic fields, solar radiation pressure and atmosphere, and a preliminary model for a generic spacecraft, including idealized *control* module, *sensors* module and *actuators* module. The Space Flight Dynamics Library takes full advantage of Modelica's reusability, flexibility and modularity features. In the next six months the Space Flight Dynamics Library will be further developed such as to include realistic models for the most commonly used aerospace sensors and actuators, and the ACS module, including blocks supervising the basic attitude determination, attitude control and control allocation functions.

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