



Performance assessment of the Space Flight Dynamics library

Deliverable 7.2

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Abstract

The Modelica Space Flight Dynamics Library provides 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 assesses the Space Flight Dynamics Library's performances in terms of modelling capabilities.

Keywords: space flight dynamics; modelling; simulation; attitude and orbit control system.

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 develop 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 was placed in the development of the model structure in order to exploit as much as possible the potential advantages of the object-oriented approach.

The Space Flight Dynamics Library encompasses all necessary utilities to ready a reliable and quick-to-use scenario for a generic space mission, providing powerful description capabilities of the space environment and spacecraft dynamics. Within the Space Flight Dynamics Library, lists of models for the most commonly used AOCS sensors, actuators and controls are available, as basic model components from whose interconnection the complete spacecraft can be quickly obtained. The Space Flight Dynamics Library thus provides the user with a very intuitive and ready for use modelling and simulation tool, specially suitable for rapid design and multi-architecture assessment of a generic space vehicle. The library's model reusability is such that, as new missions are conceived, it can be used as a base upon which readily and easily build a simulator. This goal is achieved simply by interconnecting 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). For a detailed description of the Space Flight Dynamics Library, the reader is deferred to either Deliverable 7.1 "*Design description of the library for Space Flight Dynamics*" or [4]. The present Deliverable 7.2 will mainly focus on the description of the modelling endeavor required for the completion of a fully detailed realistic case study, based on a complex spacecraft architecture for a geostationary (GEO) satellite.

2 Object-oriented modelling: building the simulator from elementary models

The object-oriented framework allows the user to build a complex system from elementary models. The complete spacecraft can thus be obtained as the interconnection of the following main systems:

- **SpacecraftDynamics:** describes the evolution in time of the spacecraft's orbit and attitude dynamics, subjected to external environmental loads;
- **Controls:** describes the attitude and orbit control systems, including algorithms for control strategies, attitude determination, data fusion, *et cetera*;
- **Sensors:** defines the actual spacecraft on board sensors;
- **Actuators:** defines the actuators set equipping the considered spacecraft.

All the aforementioned systems are abstract classes defined by dedicated interfaces, and build upon simpler models.

Let's focus on the selected case study, consisting in the design of an attitude control system (ACS) for a GEO spacecraft endowed with a single solar array rotating in the orbital plane. This configuration is chosen in reason that solar energy adsorption is maximized by adjusting the solar array orientation to the changing position of the sun. For a GEO spacecraft, this objective can be achieved in open loop by rotating the solar panels array around its axis according to

$$\theta_{sa}(t) = \omega_{\oplus}(t - t_0) - \text{atan}[\cos(i) \tan(\lambda_s(t))] + \theta_0 \quad (1)$$

where $\omega_{\oplus} = 2\pi/T_{sid}$, $T_{sid} = 23h 56' 4''$ is the Earth sidereal day, λ_s is the angle formed in the ecliptic plane between the vernal equinox and the sun position vectors, i is the inclination of the ecliptic plane, t_0 is the reference epoch (sun at Ares point) and θ_0 is the angle the solar panels array must have at t_0 to achieve full sun illumination.

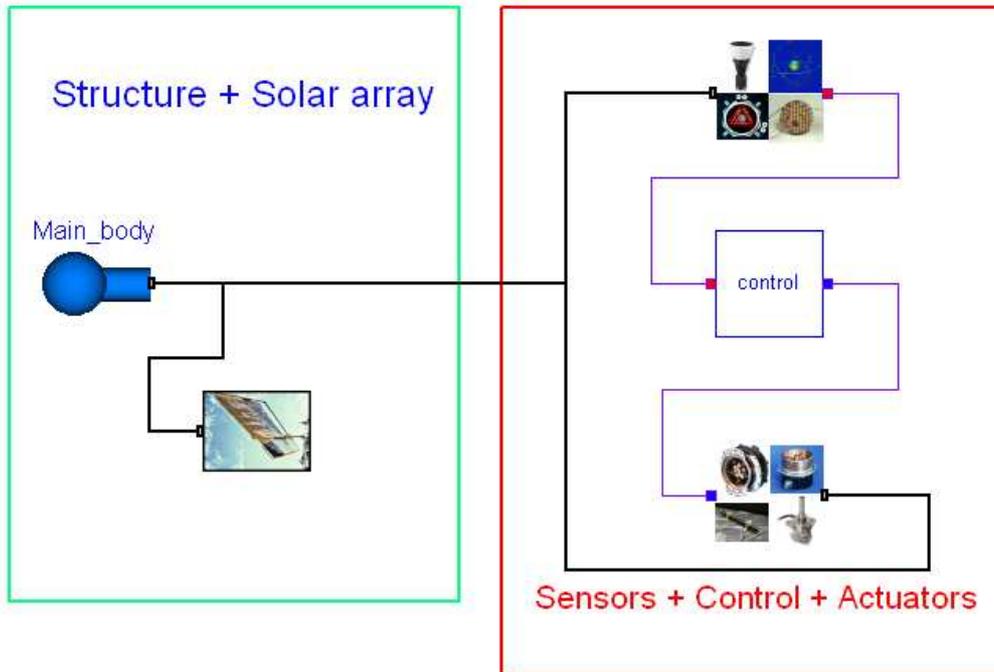


Figure 1: Layout of the considered spacecraft.

High precision attitude control for large, asymmetric spacecraft can be suitably achieved via a set of momentum storage devices, such as for instance reaction wheels (RWs). Albeit the RWs provide full three

axes controllability of the spacecraft, due to the presence of disturbance biases, such as those arising from asymmetry in the spacecraft mass distribution, angular momentum will build up in the reaction wheels, eventually reaching saturation and thus leading to loss of control authority. The removal of the excess momentum goes under the name of RWs desaturation and is achieved by means of external torques. These can be effectively provided either by magneto torquers or attitude control system thrusters, both separately or jointly, see *e.g.* [6, 1]. In reason of its inexpensiveness, the magneto torquers based, RWs desaturation is preferable, and will thus be the selected choice. Given this control architecture, the modelling of the considered spacecraft will include the following tasks:

1. Define the spacecraft dynamics. This includes the modelling of the spacecraft as the interconnection (through a revolute joint) of two rigid bodies, the *main body* and the *solar array*, and the definition of the spacecraft initial conditions (*i.e.*, orbit, attitude);
2. Define the control architecture. This encompasses the definition of suitable control algorithms to exploit both spacecraft's three-axes attitude control and RWs desaturation;
3. Define the spacecraft sensors suite. The availability of a star sensor for precise attitude reference, a GPS receiver, gyroscopes and a three axes magnetometer will be assumed;
4. Define the spacecraft actuators suite. This include the employment of a set of four pyramid mounted reaction wheels and of three axes magneto torquers exploiting the reaction wheels desaturation task.

Figure 1 depicts the considered spacecraft's layout.

2.1 Dynamics

The spacecraft dynamics was modelled as the interconnection of standard Space Flight Dynamics Library's models, the SpacecraftDynamics model, allowing for orbit-based initialization of the spacecraft orbital and angular dynamics, and a SolarArray model, based on standard Modelica MultiBody library components. The SolarArray model building blocks are shown in Figure 2, where the actuation command w_{ref} of the revolute joint of the solar array clearly obeys (1). Initial conditions are defined simply by selecting the desired orbit, simulation initial time and initial spacecraft misalignment *w.r.t.* the orbital reference frame. An alternative choice consists in the selection of the standard Modelica MultiBody initialization option, which comprises the specification of both the spacecraft's initial position and velocity vectors, initial time and relative attitude *w.r.t.* the reference frame.

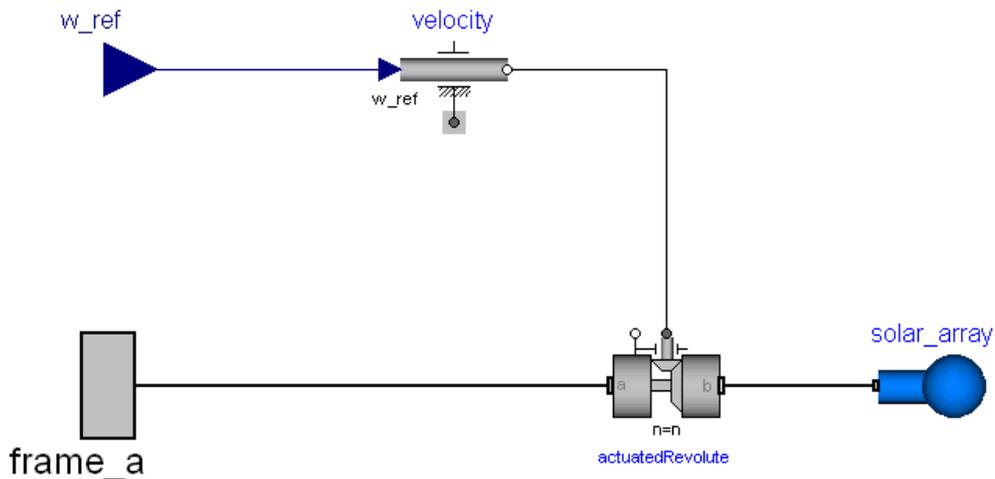


Figure 2: Solar array model.

2.2 Control

On board torques for spacecraft's fine attitude pointing are produced by exploiting the extraordinary reaction wheels (RWs) momentum management capabilities, whereas an additional set of magnetotorquers is used for achieving the RWs desaturation. The control architecture comprises algorithms devoted to the computation of the torque required to meet the spacecraft's control specification requirements, solution of the control allocation problem between the two actuator sets, computation of the required RWs angular momentum variation and magnetotorquers desired magnetic dipole. To this end, standard Space Flight Dynamics Library control components can be exploited.

The attitude kinematic and Euler equations for a rigid body's angular dynamics endowed with a set of RWs and a secondary set of electromagnetic torquers are given by

$$\dot{q} = \frac{1}{2} W(\omega_r) q \quad (2)$$

$$I\dot{\omega} + \omega \times (I\omega) + \dot{h}_w + \omega \times h_w = S(b)m + T_d \quad (3)$$

where $\omega \in R^3$ is the spacecraft angular rate, $I \in R^{3 \times 3}$ its inertia tensor, $h_w \in R^3$ the RWs angular momentum, $b \in R^3$ and $m \in R^3$ the time-varying magnetic field and magnetic dipole, $S(b)$ is the skew-symmetric matrix, $q \in R^4$ the quaternion vector parameterizing the spacecraft's attitude (described *w.r.t.* the orbital frame),

$$W = \begin{bmatrix} 0 & \omega_{rz} & -\omega_{ry} & \omega_{rx} \\ -\omega_{rz} & 0 & \omega_{rx} & \omega_{ry} \\ \omega_{ry} & -\omega_{rx} & 0 & \omega_{rz} \\ -\omega_{rx} & -\omega_{ry} & -\omega_{rz} & 0 \end{bmatrix}$$

$\omega_r = \omega - A(q)\Omega_0$, with $\Omega_0 \in R^3$ the orbital frame angular velocity, $A(q) \in SO(3)$ the attitude matrix, and T_d is a disturbance torque including gravity gradient, aerodynamic, solar radiation pressure torques, *et cetera*. All quantities are body axes referenced.

If we denote the control torque by $\tau = -(\dot{h}_w + \omega \times h_w) + S(b)m$, a state-feedback control law in the form $\tau = -[K_q K_\omega][q_1 q_2 q_3 \omega_r^T]^T$ can be devised for the linearized version of system (3), minimizing a quadratic penalty function. The RWs dynamics will then be described by

$$\dot{h}_w = S(\omega)h_w + S(b)m + [K_q K_\omega][q_1 q_2 q_3 \omega_r^T]^T \simeq S(\Omega_0)h_w + S(b)m + r \quad (4)$$

where $r \in R^3$ is a bias term due to the spacecraft's mass distribution asymmetry and applied external constant torques.

2.2.1 Desaturation policy

If a set of three orthogonal magnetic coils as secondary actuators set is considered, system (4) reduces to a linear time periodic system, of periodicity the orbital period, for which an exponentially stabilizing feedback control law in the form

$$m = \frac{1}{\|b\|^2} S(b)^T K_m h_w$$

can be easily derived, both in continuous and discrete time, see *e.g.* [2, 3, 5].

In the special case of a GEO spacecraft, system (4) can be effectively approximated by a LTI system, and the well-known results from LQR theory be applied in solving the RWs desaturation problem. This framework requires that both wheels tachometry and accurate magnetic field data are available for feedback. The latter issue is here of special concern: on a GEO orbit, the geomagnetic field is strongly influenced by the solar wind such that the Earth magnetosphere is highly asymmetric; additionally, solar storms can heavily alter the local field direction and strength. As a result, on board geomagnetic field models may be ineffective for desaturation purpose, and magnetic field measures are required.

3 Sensors

The Space Flight Dynamics Library comprises a broad choice of models for the most commonly used aerospace sensors, including several level of complexity models for the description of star trackers, gyroscopes, GPS receivers, magnetometers, sun sensors and horizon sensors. The sensor suite for the selected spacecraft can then be easily obtained by suitably connecting these standard models. The result is depicted in Figure 3.

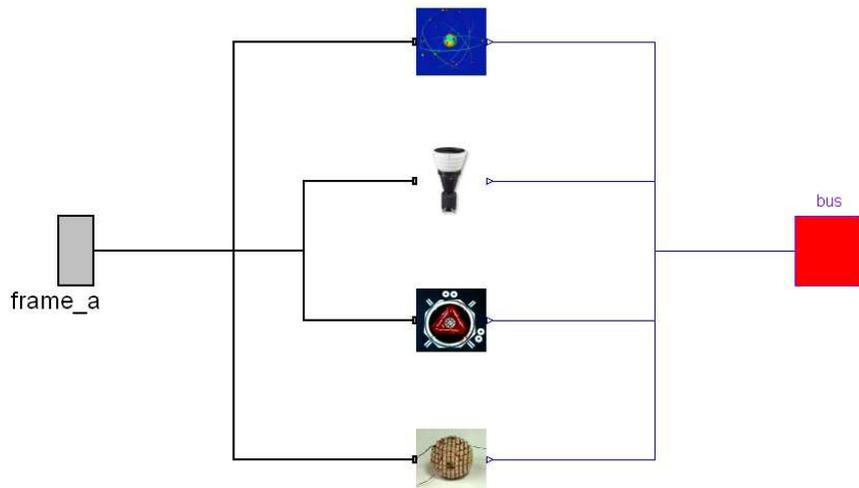


Figure 3: Sensors suite: GPS receiver, star tracker, gyroscopes and magnetometers.

4 Actuators

As for the sensors suite, the actuators set can be quickly obtained by suitably connecting standard Space Flight Dynamics Library models. The Space Flight Dynamics Library comprises a broad choice of models for the most commonly used aerospace actuators, including several actuators architecture for the description of reaction wheels, control moment gyroscopes, impulsive thrusters and magneto torquers. The spacecraft actuation system, comprising a four pyramid mounted reaction wheels assembly and three axes magnetotorquers, is depicted in Figure 4.

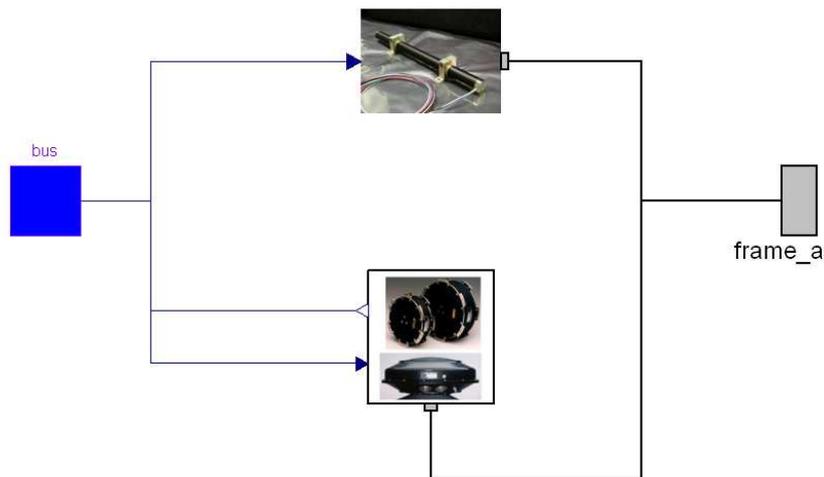


Figure 4: Actuators suite: reaction wheels and magnetotorquers.

5 Simulation results

Simulation performances are depicted and compared in the following figures. The magnetic field and solar radiation pressure data used for simulation are available online at the National Geophysical Data Center (NGDC) website¹. Specifically, the data segment used for simulation purpose (see Figure 5) was recorded by GOES-7 geostationary satellite from 4 till 8 January 1996, and is representative of standard in orbit environmental conditions. Control performances are shown in Figure 6.

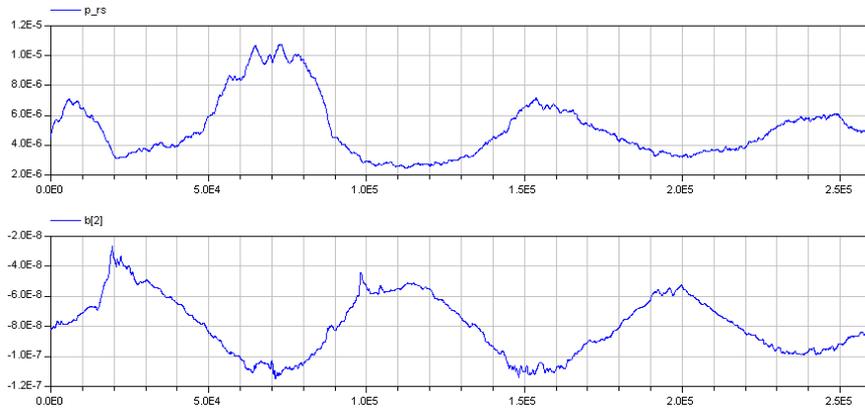


Figure 5: Solar radiation pressure and magnetic field b_2 component.

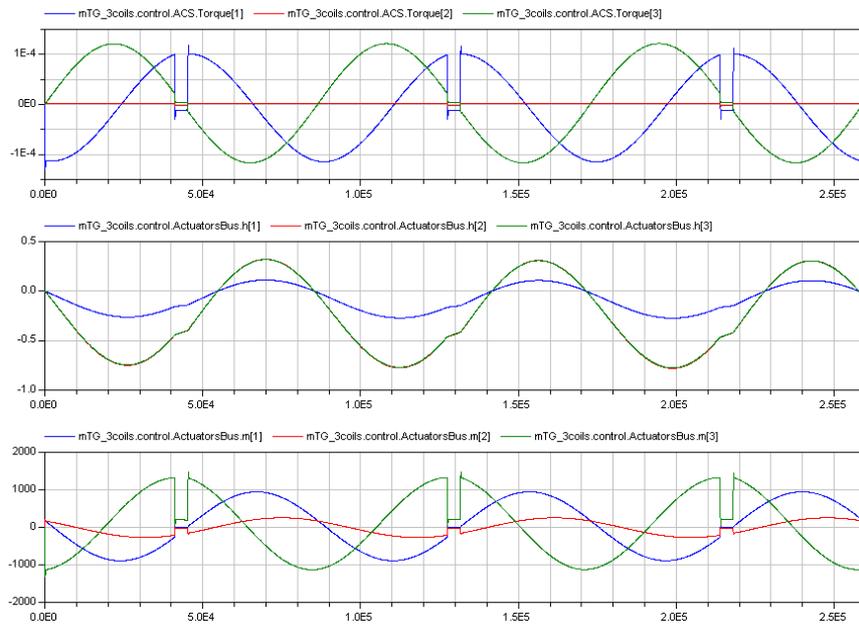


Figure 6: Control torques, RWs angular momentum and magnetotorquers magnetic dipole.

6 Concluding remarks

This report provides an assessment of the Space Flight Dynamics Library powerful modelling capabilities, which were proved in a realistic simulation case study. 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, besides detailed models suitable for the modelling of a generic spacecraft.

¹<http://www.ngdc.noaa.gov/stp/GOES/goes.html>

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