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Design and Implementation of a Space Environment Simulation Toolbox for Small Satellites

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Abstract

This paper presents a developed toolbox for space environment model in SIMULINK that facilitates development and design of Attitude Determination and Control Systems (ADCS) for a Low Earth Orbit (LEO) spacecraft. The toolbox includes, among others, models of orbit propagators, disturbances, Earth gravity field, Earth magnetic field and eclipse. The structure and facilities within the toolbox are described and exemplified using a student satellite case (AAUSAT-II). The validity of developed models is confirmed by comparing the simulation results with the realistic data obtained from the Danish Ørsted satellite.

I. INTRODUCTION

The development and design of different subsystems of a spacecraft such as attitude determination system (ADS) and attitude control system (ACS) need the availability of space environment model, in order to test and verify the different designs. Furthermore, the design approach is depended on the environment conditions and mathematical models of the space. Usually designs and tests of the subsystems are accomplished with expensive laboratory setups which limit the possibility of changing the approach without increasing the costs. Besides, each time a new project starts, the design engineer has to create the necessary model of the orbit and space environment with the required precision and features to examine and validate the designed algorithms before the laboratory verification. Therefore availability of a general purpose and configurable toolbox which includes all the necessary tools to model the environment with adjustable parameters and precision facilitates the design progress on the computer. Such a tool acts as the preliminary stage prior to the hardware implementation and physical establishment of the modules to test them in the space environment laboratory. It not only increases the success chance of the implemented modules, but also decreases the costs and design time period.

During the AAUSAT-II student satellite project, which is the second student CubeSat project at Aalborg University's Space Center in Denmark, a comprehensive and growing library containing models for the various disturbances and phenomena in Low Earth Orbit (LEO) was developed by using the MATLAB-SIMULINK(R). This work was done as a part of the satellite project.

This paper describes the structure and the facilities of the toolbox, as well as an example of using the toolbox in the design of a complete ADS-ACS system in the case of the AAUSAT-II CubeSat. Some of the simulation results are compared with the available experimental data to present the implementation accuracy of the models.

The first part of the paper explains the main library of the toolbox, the second section presents the different sub models and explains their configurable parameters and essential features. Next, the capability of the toolbox in simulating the orbit and Earth's magnetic field are examined by comparing the simulation results with the experimental measurements obtained from the Danish Ørsted satellite. Then, an example of the usage of the toolbox in designing the ADCS system is provided in the fourth section. The paper ends with the conclusion and prospects for future work in section five.

II. STRUCTURE

The toolbox provides a simulation environment for designing and testing the different subsystems such as ADS and ACS, studying the performance of the designed algorithms and contemplate the functionality of the subsystems.

There are necessary accurate models for the space environment including orbit propagators, disturbances and eclipse which are essential to consider in selecting the design approach strategies on the basis of the design criteria. Therefore the toolbox contains the following models:

- Different orbit propagation blocks, including Bl, Cowell, SGP and SGP4 orbit propagators.
- Ephemeris blocks which calculates the position of the Sun and Moon as functions of Julian date.
- Earth magnetic field block, which uses the IGRF model with configurable precision.
- Configurable disturbances blocks, including solar radiation, atmospheric drag, gravity gradient and magnetic residual which are configurable due to the necessary precision, orbit and the physical characteristics of the satellite.
- Dynamic and kinematics model of rigid body satellites.

In the toolbox library, various blocks with the relevant input and outputs represent these models. It is notable that the parameters of blocks are configurable according to a specific orbit or required precision. This property empowers the designer to change the simulation environment easily. Another essential feature of the toolbox is the interfacing flexibility of the blocks to other subsystems. It means that the designer can test ADS and ACS separately or integrated. Next section describes the individual block diagrams.

III. INDIVIDUAL SUBSYSTEMS

The toolbox is comprised of different subsystems as the blocks of the toolbox. Each blockset works independently but requires supplying necessary inputs and parameters. This gives the possibility to the design engineer to choose different models or configurations. For example, different configurations of disturbances can be made to study the behavior or performance of the designed ACS or ADS in different conditions. The blocks are divided to three category due to their usage as: Spacecraft dynamics-kinematics blockset, Environment models blocksets and Disturbances blocksets. It is essential to note that all the calculations, but the dynamics and kinematics, are in Earth Centered Inertial (ECI) reference frame which is a right-orthogonal coordinate system with the origin in the center of the Earth. The dynamics and kinematrics of the spacecraft are modeled in the spacecraft frame.

All of the subsystems are dependent on specific parameters of spacecraft and its body frame. These parameters should be predefined. The configurable parameters will be described together with each sub block.

A. Spacecraft dynamics and kinematics

The motion of a rigid body in space consists of the translational motion of its centre of mass and the rotational motion of the body about its centre of mass, thus the rigid body in space is a dynamic system with six degrees of freedom. The translational motion of the satellite is modelled in the orbital dynamic. In general, the dynamic equations of motion are given by Euler's equations for a free body. The additional inputs are the external torques from actuators, i.e. thrusters and magnetorquers and disturbances and the angular momentum of momentum wheels. The dynamic equations of motion are given by [1]. The spacecraft equations of kinematics can be described in several ways [2], [3] of which the Euler-Rodriques quaternion has the best properties for computational purposes and thus is used. With respect to spacecraft dynamics the only specific parameter is the inertia of the spacecraft which should be defined in the toolbox.

B. Environment

Different blocksets are implemented in the toolbox to simulate essential phenomena in the Low Earth Orbits.

1) Orbit propagator block: Calculating the position of the spacecraft in the orbit is the core part of any space simulation toolbox. Different orbit propagators are implemented in the toolbox which are BL, Cowell, SGP, SGP4 and DSST. NORAD's Two Line Elements are used as the initialization data for the propagators even though it can be used for the update stage. As an example, SGP4 blockset is implemented based on the Keplerian orbit calculations but also takes a number of perturbations into account, eg. atmospheric drag and spherical harmonics. The SGP4 orbit propagator calculates the position and the velocity of the spacecraft provided their initial values, mass of the spacecraft and resultant of disturbance forces acting on the body. The later is used to calculate the resultant acceleration considering the acceleration introduced by the gravity. A pure Newtonian propagation model is used to implement the propagator.

2) Gravity model block: The Earth has a non-uniform mass distribution and the gravity field around the Earth is not uniform. Therefore, depending on the position of the satellite in the orbit, the gravitational field vary. This is known as Earth's zonal harmonics [4] and its model is available in different references such as [2]. The model of gravity field is implemented and integrated in the toolbox as a blockset. The block requires the position of the spacecraft in the orbit as the input.

3) Ephemeris provider block: The position of the Sun, Moon and Earth usually are used for the attitude determination system in companion with the attitude determination algorithms and sensor measurements. Furthermore, calculation of the vector of the magnetic field and gravity gradient uses the ephemeris model of the mentioned celestial objects. This block computes the vector position of the Sun and Moon in the ECI reference frame also rotation which brings ECI reference frame to Earth Centered Earth Fixed (ECEF) reference frame given the time in Julian Date. The later, neither considers the nutation of the Earth nor its precession. These heedlesses are not crucial because one precession

revolution takes approximately 26000 years, whereas the nutation varies between ±15 with a period on 18.6 years which are practically negligible in LEO spacecrafts.

4) Albedo calculator block: Earth Albedo caused by sunlight hitting the Earth and being reflected back into space influences the algorithm of using sunsensors' measurements for attitude determination. In addition, Earth Albedo information is cradinal in the precise estimation of the power which will be generated by the solar panels. The Albedo blockset uses the information of the position of the Sun and spacecraft also the rotation of the Earth from ECI to ECEF referance frames to provide the Earth's albedo illumining the spacecraft at the moment. The blockset automatically finds if the spacecraft is obscured by the Earth and calculates the spacecraft's field of view (FOV). The algorithm uses the reflection-latitude data even it is possible to use longitude and latitude information together which highly increases the computation resources.

5) Magnetic field model block: The precise model of the Earth's magnetic field should be available as the tool for examining the functionality of the attitude determination algorithms which are based on magnetometer measurement. The standard model for the magnetic field of the Earth is the International Geometric Reference Model (IGRF). IGRF is the empirical representation of the Earth's main magnetic field. The implemented blockset receives the position of the spacecraft and computes the corresponding magnetic field vector. The order of the IGRF model's formula can be configured to change the resolution of the computation due to the required precision. The external currents in the ionized upper atmosphere and magnetosphere, which cause variations in the intensity of the Earth's magnetic field, are not considered in this blockset because the ionosphere stretches out to about 400km therefore for the Low Earth Orbits and higher ones the above mentioned phenomenon does not have considerable effects.

C. Disturbances

The disturbances which have a significant influence in a LEO are the aerodynamic drag, the solar radiation, the gravity gradient and magnetic residual [5]. In the case of the two primer the disturbance affects the geometric centre (GC) where this force results in a torque around the centre of mass (COM). For the two later disturbances, the torque is directly applied to the spacecraft as a result of external forces.

1) Aerodynamic drag: For LEO satellites the most significant disturbance is the aerodynamic drag, which originates from the coalition between gas molecules in the atmosphere and the satellite. This coalition is assumed to be an elastic coalition without reflection and is modelled according to [2]. In order to calculate the drag, the altitude and velocity of the satellite have to be known along with the atmospheric density. The atmosphere has furthermore been assumed to be stationary, since the atmospheres velocity compared with the satellites is negligible thus the resulting force is in the opposite direction of the velocity vector. The atmospheric density in this model is assumed to be spherically uniform distributed, so the only varying parameter is the altitude. A model is found by extrapolating the measured data found in [3]. The spacecraft constants used in modelling the aerodynamic drag is the size of the individual sides of the spacecraft, the drag coefficient for the individual sides and finally the displacement of the centre of mass relative to the geometric centre..

2) Gravity gradient: The uneven mass distribution of the spacecraft results in a torque around its center of mass because of the uneven gravitational pull in the spacecraft. However, this effect is not necessary unwanted. It can be maximized in a controlled manner such that the gravity gradient can be used for spin stabilized attitude control of the spacecraft. But in most satellites this torque is sought minimized either through the mechanical design or by maintaining a minimizing attitude in orbit. The gravity gradient is modelled according to [2] where the input to the model is the orbit altitude and the position of the Moon and Sun. The only constant in this model is the inertia tensor for the spacecraft. The mass of the Earth, Moon and Sun are all included in the environment constants.

3) Magnetic residual: The magnetic residual field torque is generated by interaction between the spacecraft residual magnetic dipole and the Earth's magnetic field. The spacecraft residual magnetic dipole is caused by current running through the spacecraft wiring harness and Eddy currents induced in the frame. This residual can be significantly reduced by considering the wiring during the design but is still very hard to both control and simulate since it changes significantly during the operation of the different subsystems. In the model, a static magnetic dipole moment is used to emulate the magnetic residual. The only input to this model is the Earths magnetic field strength whereas the dipole moment of the spacecraft is included in the spacecraft constants.

4) Solar radiation: In LEO, the least significant disturbance is solar radiation. The force acting on the spacecraft originates from the impulse that the photons dispatch to the surface of the spacecraft when it is hit by them. Thus the actual force that the spacecraft is exposed to is dependent on many different parameters, such as the spectral composition of the light, the satellites surface structure and optical features. Within this low orbit, these different parameters are assumed to be constant thus the disturbance is regarded as constant. This, gives the result that the only input to

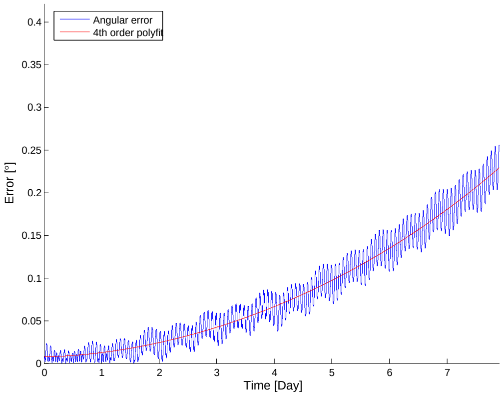

Fig. 1. Angular error of the toolbox SGP4 model compared to the true GPS position measurements of Ørsted satellite

the model is the spacecraft orientation and the position of the Sun and the Earth in order to calculate when the spacecraft is in eclipse [2]. In order to facilitate the different structural compositions of a spacecraft it is possible to specify the size and reflection coefficients for each of the sides among the spacecraft constants.

IV. VERIFICATION

The development and implementation of the various blocksets are done based on the mathematical models and the configurable parameters as described in the previous section.

In order to verify the implementations of the different subblocks in the toolbox real satellite measurements have been used. As two examples, evaluation of SGP4 orbit propagator model as well as the IGRF model are presented.

A. Orbit propagator validation

The most important block in any space environment simulation is the orbit propagation subblock which is verified along with the Earth's magnetic field model.

The data used for these two tests originates from the Danish research satellite, Ørsted. The data used in these tests is obtained during two days from before midnight on the 9^{th} to midnight 10^{th} of February 2002. The corresponding TLE at this period is shown below:

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ORSTED
1 25635U 99008B   02039.19776638  .00002964  00000-0  76752-3 0  5333
2 25635  96.4789 110.2920 0148581  79.4653 282.3232 14.43879506155754
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Ørsted TLE for the 9^{th} of February 2002

The Julian date corresponding to the first data in the obtained dataset is: $JD_{sim} = 2452315.485$ and is used as the initial condition throughout the tests.

The verification of SGP4 model is presented here as an example to show the accuracy of the bulit-in models. The position of the Ørsted satellite calculated from GPS position measurements is used as the reference. Due to the high precision of the GPS measurements, the error of the position determination of Ørsted satellite is neglected. Figure 1 depicts the angular error of the SGP4 model compared to the true position measurements. The mean of the error remains under $0.2\circ$ for 6 days.

B. Magnetic field validation

The implemented IGRF model delivers the magnetic field of the Earth on the orbit. To examine the accuracy of the implemented IGRF model, the magnetic field measurements of Ørsted satellite are used as the true values. Time stamps of each measurement are available in the data package. Figure 2 presents the angular error caused by the divergence of the model from the true measurements. In practice, the error of the IGRF model is not independent of the orbit propagator error. Figure 3 presents the angular error of IGRF model along the orbit propagation by SGP4 block diagram. The Ørsted data is used as the true measurements. The results of the simulations confirm the precision of the implementations.

V. AAUSAT-II CUBESAT CASE STUDY

As an example of the capability of the toolbox to handle real simulation scenarios, its functionality in the design and development of ADS and ACS subsystems of AAUSAT-II student CubeSat is described. AAUSAT-II satellite's mission is to carry a new Gamma Ray Burst detector made by Danish Space Research Institute. The satellite project has passed the design phase with the aid the space environment simulation toolbox in the design of the control and navigation system. The ADCS of AAUSAT-II is based on gyro, magnetometer and sun sensor measurements for attitude determination and momentum wheels and magnetorquers as the actuators to control and navigate the spacecraft. The CubeSat is designed for a LEO. Therefore the toolbox were configured for the specified orbit.

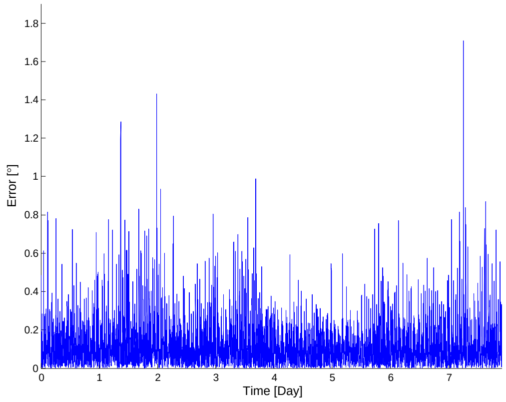

Fig. 2. Angular error of the IGRF model compared to the true magnetinc field measurements of Ørsted satellite

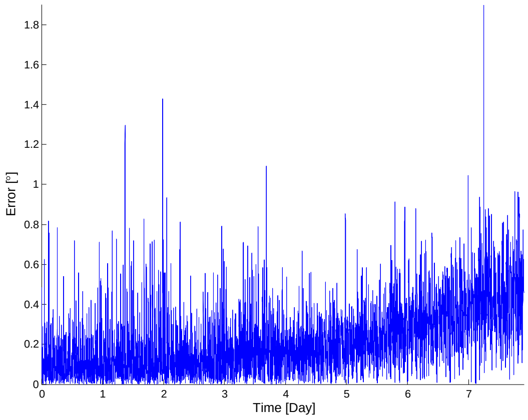

Fig. 3. Angular error of the IGRF model along the SGP4 orbit propagator compared to the true magnetinc field measurements of Ørsted satellite

In the ADS design phase, the determination algorithms based on an Extended Kalman Filter were designed and tested with the aid of the toolbox. Sensor emulation blocks for gyros, magnetometer and sun sensor were developed to be used in cooperation with the models of the dynamics and kinematics, magnetic field, ephemeris and albedo. Different disturbances on the measurements were added to certify the functionality of the determination system. In the other hand, the algorithms for controlling of the actuation system was also developed, with the aid of the toolbox, to simulate the dynamics and kinematics of the satellite in the detumbling mode and pointing, separately. Availability of the toolbox helped to add the effects of the disturbances to study the functionality of the ACS algorithms.

After all, ADS and ACS blocks were integrated into a unique model consisting the model of the space environment and the algorithms of the navigation system designed by the responsible teams of Master students. Figure 4 shows the principles of integrated simulation environment to test ADS and ACS in navigating the satellite.

VI. CONCLUSION

In this paper, a space environment simulation toolbox was introduced which is a growing library containing models for the various disturbances and phenomena in Low Earth Orbit (LEO), developed by using the MATLAB-SIMULINK(R). The toolbox includes, among others, models of orbit propagators, disturbances, Earth gravity field, Earth magnetic field and eclipse.

To evaluate the precision of the implementations, three tests were presented which confirmed the precise functionality of the models. As a case study, the design, implementation and test of ADS-ACS system of AAUSAT-II CubeSat was briefly introduced which shows the practical advantages of the toolbox. It is strongly believed that the space environment toolbox efficiently improves and eases the design, simulation and test of ADS-ACS system for LEO satellites.

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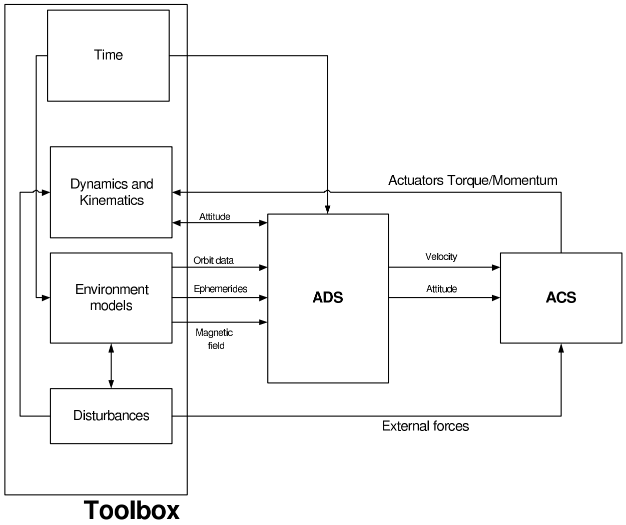

Fig. 4. An example of integration of the toolbox in the design and simulation of ADS and ACS systems in the case of AAUSAT-II satellite