MOON ORBITER SIMULATOR FOR THE ESA PROJECT ESMO

Matevž Bošnak, Sašo Blažič, Drago Matko

University of Ljubljana, Faculty of Electrical Engineering
1000 Ljubljana, Tržaška 25, Slovenia

matevz.bosnak@fe.uni-lj.si(Matevž Bošnak)

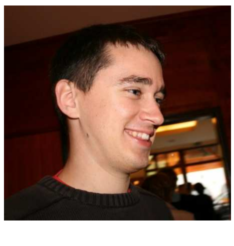
Abstract

The European Student Moon Orbiter (ESMO) is planned to be the first European student mission to the Moon. ESMO represents a unique and inspirational opportunity for university students, providing them with valuable and challenging hands-on space project experience in order to fully prepare a well qualified workforce for future ESA missions in the next decades. ESMO student teams, supported by faculty staff, will produce a complete spacecraft from scratch. Its mission will be to fly towards the Moon, enter Moon's orbit and execute scientific experiments while orbiting around the Moon. These experiments will be performed with the narrow angle camera, the microwave radiometer and the radar as main spacecraft's payload. As a part of the ESMO project, a Functional Engineering Simulator (FES) will be produced that will allow the project teams to model the spacecraft functions and performance at various stages in the mission and simulate the operational environment including ground station contacts. The simulator is critical to verify the correct sizing of subsystems in the design and the identification of adequate design margins and criticalities, especially in worst case scenarios and in the presence of failures leading to off-nominal situations. It will also be used to determine the telecommands to be generated, test for potential failure and recovery scenarios and provide overall validation of the system functions including data handling and attitude control. In this paper a concept of FES will be presented along with the work that has already been done on the subject.

Keywords: European Student Moon Orbiter, Functional Engineering Simulator

Presenting Author's Biography

Matevž Bošnak graduated in 2009 on the Faculty of Electrical Engineering, University of Ljubljana. Now he works as a PhD student in the Laboratory of Autonomous Mobile Systems at the same faculty.



1 Introduction

With the launch of the first artificial satellite around 50 years ago and entering the space, human stepped onto the whole new path of science. It enabled us to look down on Earth from space, communicate between continents and travelling and living on other celestial bodies in our near space.

With joined powers, Europe put itself into a leading role of technological progress and development in space science. What each of the countries could not achieve by their own, was possible through European space agency, ESA. Today, Europe has one of the most successful rocket launchers, explores the universe with the biggest and most powerful telescopes and discovers our neighboring planets with autonomous space probes. Such a success would not be possible without technological research and appropriate infrastructural investments and interest in sharing the knowledge [1].

Space exploration oriented projects are mostly quite complex and must be very well organized and managed. To solve this issue and provide the engineers with the clear instructions on how to follow the path of project management and design, a set of ECSS (*European Cooperation on Space Standardization*) standards was published. These documents provide course of work in all phases of the project. In general, each project is divided into phases 0/A to F and includes Mission Analysis and Feasibility (Phases 0 and A), Preliminary Design (Phase B), Detailed design (Phase C), Production and validation (Phase D), In-Orbit Operations (Phase E) and Mission termination (Phase F) [2].

European Student Moon Orbiter (ESMO) is a third project of the ESA Education Projects Unit and its purpose is to lead European students in designing and producing the spacecrafts. If successful, this will be the first European spacecraft, built by the students to leave the Earth and then enter the orbit of another celestial body. Spacecraft will be developed till 2014 and launched to the Moon, where scientific measurements with a microwave radar and a radiometer[3] will be made and pictures of lunar surface by means of a narrow-angle camera will be produced. In lunar orbit an experimental system called LunaNet will be activated, which will offer a communication similar to the internet on the Moon.

The ESMO project is based on more than 200 volunteer students coming from 10 European countries and a small proportion of faculty staff who manage the work of student teams. The work on the ESMO project is divided between the teams at 19 European universities and is the first project of a such nature [4]. The main objectives of the ESMO project are [5]:

- To launch the first lunar spacecraft to be designed, built and operated by students across ESA Member States and ESA Cooperating States.
- To place the spacecraft in a lunar orbit.
- To acquire images of the Moon from a stable lunar orbit and transmit them back to Earth for education outreach purposes.
- To perform measurements relevant to advanced technology demonstration, lunar science and exploration.

The ESMO project started in 2006 with the selection of participating universities and their proposals. Based on these proposals, the project feasibility study was carried out in which the feasibility of the overall mission and the individual systems and subsystems was verified. On the basis of approved proposals the University of Madrid began systematically collecting the data on individual subsystems in order to gather documentation for the construction of the simulator. In 2009, a team from the University of Ljubljana took over the development of the simulator. Universities in Slovenia also participate in development of the On-Board Data Handling Unit and the radar payload unit.

In 2009, the project was handed over to the company SSTL (Surrey Satellite Technology). SSTL has a reputation of many successful constructions and launches of small satellites. By taking over the ESMO project, they represent the insurance that the spacecraft will be built and launched, following the planned schedule.

The functional engineering simulator is an important tool in mission planning and verifying the energy and $\triangle$v-budget ($\triangle$v-budget is an astrogation term used in astrodynamics and aerospace industry for velocity change (or delta-v) requirements for the various propulsive tasks and orbital manoeuvres over phases of a space mission[6]) which are closely linked to the cost of the mission. Analysis of those budgets enables engineers to minimize the costs. This article presents the ESMO project with details in construction and operation of the simulator.

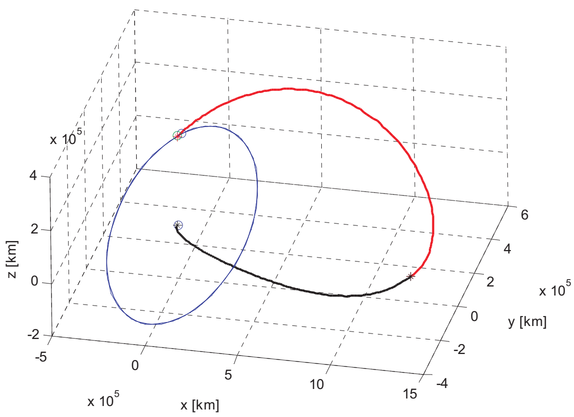


Fig. 1 Orbiter trajectory

2 The mission

The mission starts with the release of the orbiter from the launch vehicle in the GTO (Geostationary Transfer

Orbit). The most important manoeuver in this phase is then executed. Omni-directional communication unit is activated and the spacecraft is instructed to perform detumbling procedure and attain a stable orientation of solar panels towards the sun. This will help in providing power to all subsystems for in-orbit satellite commission operations. During these operations each subsystem will be tested in order to verify that the subsystem is working as expected [5]. In order to reduce the spacecraft radiation dose it is preferred that this step is not delayed over 4 weeks time.

In the next mission phase main engines will be activated and spacecraft will be accelerated away from the Earth towards the unstable Sun-Earth Langrange L1 point. The Sun-Earth Langrange L1 point is a point where the gravitational forces of the Earth and the Sun are equal. When at point L1, the spacecraft is closer to the sun and it is still circulating with the same orbital period as the Earth. Additional manoeuvres will be performed when the Moon is in a favorable position and the spacecraft will then be accelerated towards it. This trajectory (Figure 1) has been chosen because of the need for a smaller Δv on the expense of the longer travel time.

In the third phase of the mission, the focus will be given on the maneuvers, which are necessary to successfully lock the spacecraft into an elliptical lunar operational orbit with the perilune of about 100 km above the south pole of the moon. This mission phase will be followed by the main, operational, phase of the mission, in which payloads will be activated and scientific measurements will be produced. Lifetime of the spacecraft in lunar orbit is estimated to six months. The mission will be completed with the last phase when the spacecraft will crash into the moon because of orbit height deterioration.

Currently, the ESMO project is in the phase B, therefore it is experiencing many changes, especially in hardware selection.

3 The ESMO spacecraft structure

The ESMO spacecraft (Figure 2) will have two large perpendicular solar panels that will normally be oriented towards the sun. Propulsion, radiators, communication and other systems will be housed behind these solar arrays. The whole orbiter will weight approximately 300 kg (exact spacecraft's dimensions, shape and mass may still vary during the initial phases of the ESMO project).

Because of the mass and moderately small size of the spacecraft is classified as mini-satellite and will be launched as a secondary payload on one of the launch vehicles (again, due to early mission phase, exact launch vehicle selection is not yet available).

Main propulsion will be based on standard bipropellant rocket engines that burn liquid Monomethylhydrazine (MMH) fuel and Mixed Oxides of Nitrogen (MON) as an oxidizer. Those chemicals will be stored in two separate tanks and at activation, compressed nitrogen gas (also called cold gas) will be used to push them out.

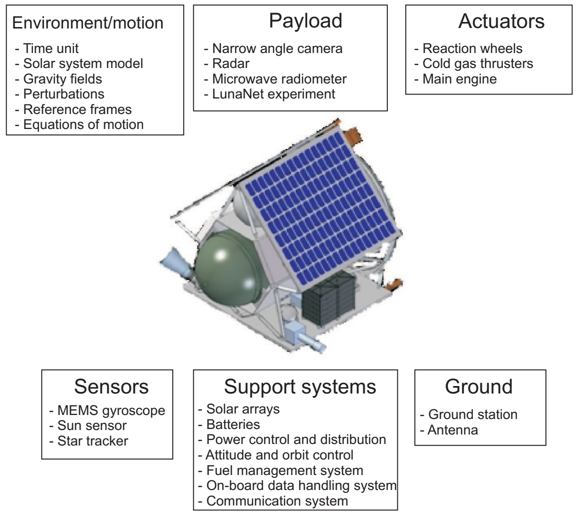


Fig. 2 Graphical representation of the ESMO orbiter

Nitrogen gas will also be used for crude attitude maneuvers with the help of four cold-gas thrusters in the form of the Vernier thrusters. These will be used mainly in detumbling operation and for reaction wheel desaturation. Reaction wheels are electro-mechanical actuators that use the large flywheel mounted to an electric motor to transfer the angular momentum between the entire spacecraft and flywheels because of the conservation of the angular momentum. To improve redundancy of the whole system there is a need of more than two reaction wheels. The study is being made whether to include three or four in the ESMO orbiter.

Sensory part of the orbiter will consist of sun sensors, star trackers and a MEMS rate sensor. The sun sensor uses four light detectors housed behind a slot in the case. The position of the sun is calculated based on the illumination of each of the detectors. Star tracker sensor uses the catalogue of the known stars and their positions on the sky and compare these with the image produced by the sensor camera. Together with the MEMS rate sensors that detect the rotary speeds of the spacecraft, these sensors provide accurate measurements of the spacecraft's attitude.

The autonomous operation of the vessel will be ensured with the help of advanced solar cells mounted on the front two sides of the vessel. By turning these two sides towards the sun at the angle of 45 degrees, each panel will receive the same total power and the maximum solar illumination of the spacecraft will be achieved.

Power from the solar panels will be transferred to the main power bus that will primarily power all onboard systems. In cases when the generated power will be greater that the one required by the systems, onboard 6-Ah Lithium-Ion battery pack will be charged to provide uninterrupted power supply for normal operation in eclipses and short-term operations of the subsystems with high power consumption (e.g. communication system, radar, reaction wheels operations, etc.). These batteries will also be pre-charged to allow initial operations in the orbit before solar cells could be pointed towards the sun.

Main payload for this mission will be a narrow-angle camera, which will be used for taking pictures of the lunar surface from a height of approximately 200 km. Additional payloads may also be installed in the orbiter after the mission mass budget evaluation. If the mass budget will allow additional payload to be carried to the moon, a passive radiometer to measure the temperature of the lunar regolith a few meters below surface or pulse frequency modulated radar may be selected. The radar could be used for scanning the surface of the moon or even for a high speed communication link with the ground station.

4 The ESMO FES tasks

The main task of the ESMO FES simulator is simulation of a complete spacecraft with all subsystems. The simulator must be able to accurately simulate movements in the GTO orbit (Geostationary Transfer Orbit), the lunar transfer trajectory and the operational lunar orbit. Special focus is given on simulation of on-board power system, forces and torques produced by the actuators and control system that regulates the spacecraft's attitude and orbit. Therefore the ESMO FES simulator must allow the simulation of all maneuvers with the propulsion system. The results of this simulation will show if the system is properly sized and if the Attitude and Orbit Control System (AOCS) is properly configured to provide the desired position and orientation of the spacecraft. The simulator must also provide means to analyze Δ-v and energy budgets and provide an insight into the amount of power generated and consumed in different conditions the spacecraft may encounter during the mission.

It will be possible to simulate different failure modes easily and cost-free, thus providing the mechanism to analyze overall spacecraft's robustness. Various failure modes can be specified for each subsystem – from power system, sensors, actuators to communication, payload operation and on-board data handling units.

ESA and SSTL produced a list of simulator use cases and their specifications. Primarily, simulator will be used for system requirements consolidation, key algorithm validation, trade-offs evaluation, system preliminary design support, performance verification and identification of appropriate thresholds and critical points [7].

5 The structure of the ESMO FES

Since the work on the spacecraft itself is divided into functional subsystems, the same subsystem's organization was included in the simulator. The work on the simulator was divided among 10 teams of students who have freely chosen the subsystems.

These student teams were instructed to examine the documentation already prepared and to complete and correct it accordingly. Other ESMO student teams working on each spacecraft's subsystem were instructed to provide us with the simulation models that they produced for their own low-level subsystem analysis. Some simulation models were received but most of the subsystems models we needed to produce on our own on the basis of the subsystem's documents. These are simplified models and will be updated or replaced with more sophisticated ones in further development of the simulator with the help of other teams.

The FES simulator for the ESMO spacecraft is built entirely in Matlab/Simulink. Simulation models of subsystems are realized in the form of a simulation scheme in Matlab Simulink and Stateflow environments. Besides the tools used, ESA also specified that only standard Matlab Simulink libraries should be used. Therefore, most of the FES relies on basic blocks (integrators, gains, sum and multiplication blocks, etc.) and Embedded Matlab Function blocks where a more advanced algorithms are coded in Matlab Embedded code. Overall simulation scheme is grouped into functional subunits. The selection of different combinations of active subsystems is possible to adjust the simulation to the specific use case.

The construction of simulation models requires some deeper knowledge of the simulators inner workings and therefore represents a serious barrier for the teams constructing real subsystems in producing appropriate simulation models [8]. On the contrary, simulation team does not have a deeper knowledge on inner workings of a specific subsystem. This problem was in some cases successfully resolved with a lot of communication and cooperation between the simulation team and real-system teams.

Some models we received from real-system teams had inappropriately high model fidelity and contained many algebraic loops. In order to resolve these issues, some model simplification and reorganization was needed. This task was not simple and took many man-hours of work.

An even greater problem, however, represents the integration of simulation models, which contain very different time constants. This produces the so-called stiff systems, which represent a unique problem in successful implementation into the simulator. In order to correctly simulate models with small time constants, the calculation step has to be reduced, leading to a reduction in the performance of simulation runs and increases the problem of numerical integration errors.

Such situations are not easily solved, so we decided to conditionally include models of individual subsystems in the final simulation. Simulation models, which contain very short time constant will be included only in scenarios where these models are activated (e.g. activating the main engines or cold gas thrusters) [9].

The end user is presented with the graphical user interface (GUI) to hide complex Simulink simulation scheme. All operations needed to simulate use cases specified can be carried out through this GUI or via command line command that receives different param-

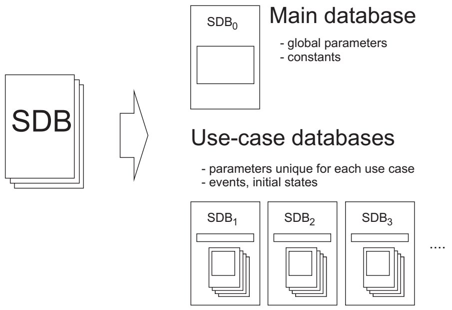


Fig. 3 System database structure

eters to select the appropriate configuration of the simulator. Predefined scenarios can be scripted in system database and activated during the simulation. By defining different scenarios in system database, test results can be reproduced any time and are not dependent on user running the simulation. Interaction between end user and simulation run is limited to controls to initiate, pause, resume or stop the simulation.

System database (Figure 3) is realized in a form of Microsoft Excel spreadsheets to enable easy editing possibilities and provides an overview of contents. The use of a SQL database is not necessary since database is never edited by multiple users at a time. Entries in the database are spread and organized in multiple files. One file is used as a main system database that contains universal constants, system configuration and similar parameters that are considered as constants. Additional files are used to hold use case specific parameters that the end user can change to simulate different scenarios. In user eyes, the main database file is considered as read-only, while the other files can be read or written to.

Each record in the database has its own unique identifier that is derived from the subsystem name, where the parameter is used, parameter name and dimensions of the parameter. Dimensions are omitted for scalar records. Every record has also a field for value, measurement unit and description.

Each simulator use case scenario is defined in its own additional database file that has a similar structure to main database file. Besides defining the specific parameters values, there are additional tables in which system's initial states, logged signals and custom events are described. Initial states specify the state of the system at the beginning of the simulation run. Simulation results are saved with the help of logging the selected signals during the simulation, resampling and saving them to a comma separated values (CSV) file. With the help of the custom events, the user can specify a time-dependent signal that would enter the simulation. This can be used to trigger system activation or induce failures during the simulation in order to observe how the system handles them. Various additional commands can also be simulated this way instead of relying on communication system (e.g. telecommands sent from the ground station).

This enables the user to efficiently simulate each case specified in use case document. The user can selectively turn on or off each subsystem in order to include or exclude it in the simulation run.

6 The simulation run

The simulation of a selected scenario begins with describing it in the system database. A new set of four tables must be created - lists of constants, logged signals, events and initial states. The user must also specify time interval of the simulation, sampling times and some additional parameters that affect simulation execution.

By changing the values of initial states, spacecraft can be put in a desired state. Position, speed, orientation and other system and subsystems states at the beginning of the simulation can be specified with simple entries in the database.

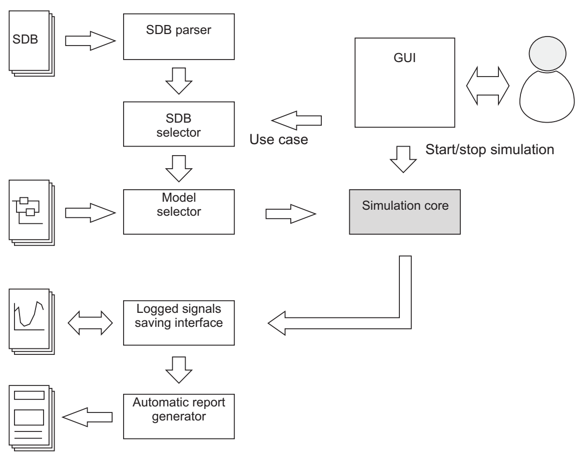


Fig. 4 The structure of the simulator

The simulation of the ESMO spacecraft (Figure 4) is started with the main M-script file that collects data from the user. This data is fed to a series of database loaders and parsers, that load the data from the database file, analyze the data, check for errors and imports the values into the Matlab workspace environment. Values are stored in variables, named after unique identifiers of data stored in the database. Variables are declared as base global variables, therefore they can be retrieved anywhere inside Matlab environment. The same goes for the events structures that are also created globally.

The simulated experiment is divided into several stages that span the time-length defined in the database as a simulation parameter. The first simulation stage is started after successful environment initialization and uses the initial states' values defined in the system database. After one stage is simulated with variable time step ode45 integration method, all final states are recalled from the Simulink memory space and stored in Matlab base workspace. Additionally, all relevant signals' values are also recalled, resampled and stored as a CSV file. The list of the relevant signals is generated dynamically before simulation based on entries in the system database. These values enable the post-simulation analysis. Simulation continues with the next simulation stage until the stop condition is met.

At the end of the simulation, the analysis of generated results begins. The data is loaded from the results file line by line and analyzed regarding to the user requirements. Automatic report generation system is then used to automatically create a report of a simulation run that includes time, date, purpose of the simulation run and other graphical, text or tabular forms of representing results. A list of all parameters values can also be included in the report.

7 Documentation issues

An important aspect of participation in projects such as ESMO is the documentation system. Since this is a project involving a large number of people, that is changing rapidly because of students entering the project and those leaving, well prepared documentation is the basis for the exchange of information. In designing the FES simulator a lot of cooperation with other teams is needed, since, as mentioned before, they have deeper knowledge about each subsystem that is being simulated. This cooperation started with the production of initial specifications of the subsystems that each team was instructed to provide.

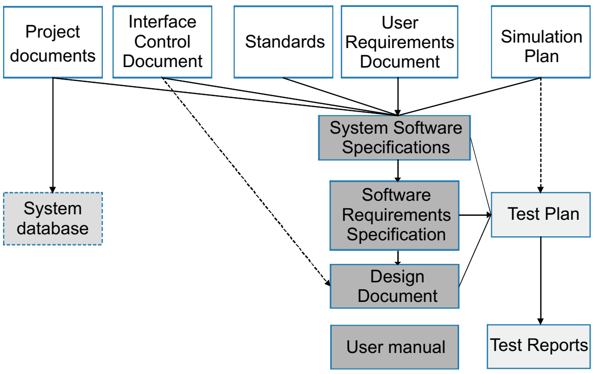


Fig. 5 Documentation overview

Documentation of the FES contains some specific documents that are related only to executing simulation tests. These documents are required to specify in details how the subsystems' models are designed, give detailed simulator architecture specification and list the simulator use cases that are possible through usage of the simulator. In the final phase of the simulator development, a detailed user manual will be produced that will contain instructions for the end user on how to use the simulator. This user manual will specify hardware and software requirements to run the simulator, explain the structure and procedures to edit the system database, briefly explain the system model in use and give clear instruction on how to execute simulation runs and use automatic report generation system.

Structure of documentation is based on ECSS (The European Cooperation for Space Standardization) standards tailored for the ESMO project. Overview of these documents can be seen in Figure 5.

8 Conclusion

Taking part in a project such as ESMO enables participating students to gain knowledge in the field of building spacecrafts, managing projects, taking care of documentation process and especially working together with others. During the study, a lot of this knowledge is already gained but mostly in theoretical forms. With participation in the ESMO project, which is mainly educational in its nature, this theoretical knowledge is put into practice.

Through the ESMO project, ESA is also trying to raise public interest in space science and to find and train future space scientists. To successfully build and launch satellites and other spacecrafts, many different branches of scientists are needed. Our group is specialized in simulation problems and is involved in design of a Functional Engineering Simulator that will be used to test and verify different spacecraft's subsystems.

9 References

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