

Mission analysis of nanosatellite constellations with OpenSatKit

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Abstract

CubeSat reliability is still considered an obstacle due to the sizeable fail rates generally attributed to the dead-on-arrival cases and early subsystem malfunctions. Thus, as CubeSats' primary purpose moves from technological demonstrations and university projects to missions where a significant risk of failure is not acceptable, an inexpensive method to emulate low Earth orbit constellations is being researched.

The results presented have been developed in the framework of the PLATHON research project, which intends to develop a hardware-in-the-loop emulation platform for nanosatellite constellations with optical inter-satellite communication and ground-to-satellite links. Consequently, a crucial aspect of this project is to have a sufficiently precise orbital propagator with real-time manoeuvring control and graphical representation.

NASA's OpenSatKit, a multi-faceted open-source platform with an inbuilt propagator known as 42, has been chosen to analyse the programme's feasibility in order to create a constellation testing bench. As an initial development of a software-in-the-loop application, the pre-processing of files has been automated; enhanced Attitude Determination and Control System manoeuvres have been added and configured through bidirectional socket interfaces, and the results format has been modified to be easily post-processed with MATLAB and Simulink.

Keywords

Constellations, Inter-Process Communication, Nanosatellites, Orbit Propagation

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Acronyms/Abbreviations

ACS	<i>Attitude Control System</i>
cFS	<i>core Flight System</i>
GNSS	<i>Global Navigation Satellite System</i>
GS	<i>Ground Station</i>
GUI	<i>Graphical User Interface</i>
HiTL	<i>Hardware in the Loop</i>
IoT	<i>Internet of Things</i>
IPC	<i>Inter-Process Communication</i>
LEO	<i>Low Earth Orbit</i>
NASA	<i>National Aeronautics and Space Administration</i>
NS3	<i>Network Simulator 3</i>
PLATHON	<i>Integrated Hardware in the loop simulation Platform of Optical communications in Nanosatellites</i>
SiTL	<i>Software in the Loop</i>
SSH	<i>Secure Shell Protocol</i>
TLE	<i>Two-Line Element</i>
ECEF	<i>Earth-centred, Earth-fixed</i>
ECI	<i>Earth-centred inertial</i>

1. Introduction

Since the beginning of the space age, satellite design philosophy was dominated by conservative designs built with highly reliable components to endure extreme environmental conditions. During the last two decades, the dawn of the CubeSats has changed this philosophy, enabling a whole world of new possibilities.

The deployment of monumental CubeSat constellations in low Earth orbit (LEO) is set to revolutionise the space sector by enabling faster and more economical innovation cycles. However, CubeSat reliability is still considered an obstacle due to the sizeable fail rates among universities and companies, generally attributed to the dead-on-arrival cases and subsystem malfunctions [1]. In recent years, increased flight experience is changing this trend, and future testing systems are set to considerably reduce the probability of any malfunction.

Mission Analysis is the design and analysis of satellite orbits such that the objectives of a space mission are achieved in the best possible way. Among the main tasks and outputs, this research has focused on ground station coverage, communication angles and distances

between satellites, as well as eclipses and distance from the Sun, which are crucial to power subsystem manoeuvre strategies.

The results presented in this paper have been developed in the framework of the Integrated Hardware-in-the-loop (HiTL) emulation Platform of Optical Communications in Nanosatellites (PLATHON, from the Spanish acronym). This research project intends to develop a Hardware-in-the-loop emulation platform for nanosatellite constellations with optical inter-satellite communication and ground-to-satellite links.

Section 2 summarises the state of the art and programme selection, section 3 enumerates new programme contributions during all simulation stages, section 4 shows the results of the new features, and section 5 concludes with the current state of the project and potential improvements.

2. State of the art

In order to propagate orbits, there are open-source and private programmes that can perform the simulations with a wide range of detail depending on the project requirements. Among the available open-source options, the National Aeronautics and Space Administration's (NASA) OpenSatKit has been chosen because it offers HiTL capabilities and can be easily customised to interact with the project's models. Thus, as the programme is open-source, it is helpful for research and development purposes, and introduces students and professionals to the space sector.

2.1. OpenSatKit

OpenSatKit is a multi-faceted platform that combines three independent programmes [2]: Ball Aerospace Corporation's COSMOS command and control platform for embedded systems; NASA's core Flight System (cFS), a platform and project-independent, reusable software framework; and NASA's 42, a comprehensive, general-purpose simulation of attitude and trajectory dynamics and control which can be applied to numerous spacecraft composed of multiple rigid or flexible bodies [3].

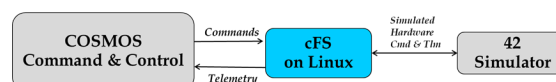


Figure 1. OpenSatKit platform connectivity [4]

This study aims to analyse the feasibility of NASA's 42 orbital propagator in the PLATHON project and its connectivity with OpenSatKit modules.

2.2. PLATHON

Figure 2 portrays PLATHON's software applications, combining NASA's 42 and Network Simulator 3 (NS3), as well as with HiTL connections to the CubeSat test devices.

NS3 is a discrete-event network simulator containing precise communication channel models between nodes to calculate the optimal route between two points.

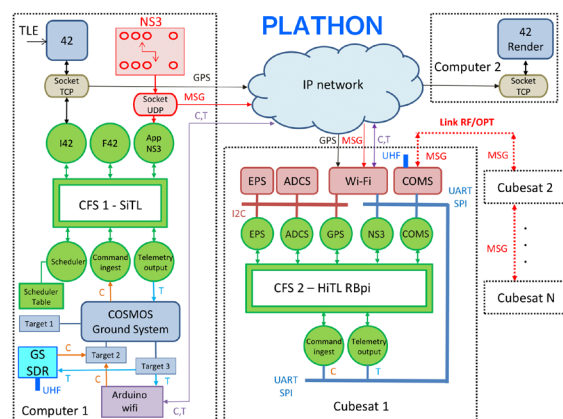


Figure 2. PLATHON project diagram

This prospective example considers a set of satellites that collect data from the Internet of Things (IoT) networks located across the world in areas inaccessible to the internet and relays the data to a connected ground station (GS) in an optimal way.

Since the communication system nodes are mobile, and their communication state changes with the satellite's time, position and attitude, it is necessary to calculate the previous possible routes at each point of the orbit.

For this purpose, it is necessary to simulate the mission with the OpenSatKit system and transfer the results to the NS3 so that it establishes the optimal routes for each position, taking into account all satellite positions as well as those from the IoT and GS, which will also be mobile due to Earth's rotational movement.

3. Programme contributions

Some programme modifications and new features are highlighted, and these are divided based on their relative position within the simulation.

3.1. Pre-processing

Due to the fact that 42's input variable system is based on structured text documents, where each file performs a specific function, it is necessary to automate the process for large satellite constellations. Thus, a MATLAB-based

code has been developed to read database files and create the essential input files.

Furthermore, a capability to read two-line element sets (TLE), which is a data format encoding a list of orbital elements of an Earth-orbiting object for a given point in time, has been set to simulate current constellations with the latest available data. TLE constellation records are extracted from CelesTrak [5] and transferred to 42-readable document files within seconds.

3.2. 42 files and ACS

Initially, 42 is only set to save all spacecraft's dynamic and kinematic states, whilst most of the remaining properties are only kept for the first simulated body. Thus, the programme has been modified to be able to select and store the simulation data for every spacecraft. Depending on the magnitude of the constellation, a preselection of a pertinent memory allocation loop defines the maximum number of bodies to analyse. The concurrent number of active files has been modified for Linux OS versions as the files are created simultaneously at the end of the simulation.

Conditional on the purpose of the simulation, two 42 variants are defined; one for post-process data analysis and another for real-time communication with the Software in the Loop (SiTL) and HiTL capabilities

The simulator contains several basic attitude control subroutines, ranging from passive to active control. However, based on the Prototype control mode function, in which the satellite adjusts its attitude using a Proportional Derivative controller, new Attitude Control System (ACS) functions have been wholly reassembled to suit PLATHON's hardware models. The manoeuvres explored by these models are coarse and fine pointing with reactions wheels, as well as pointing and detumbling with magnetorquers.

Basic sensors and actuators are included. The truth value is tampered with noise and bias in the sensor models to simulate real-system distortion. At the same time, the maximum torque limits the actuator models according to the product specifications. In order to replicate the PLATHON's hardware currently under development, the laboratory specifications have been set to obtain reliable results.

The primary attitude control function is capable of determining the satellite's attitude with sun sensors, star trackers or gyroscopes, and adjusting it accordingly with a 3-axis stabilised system based on either reaction wheels or

magnetorquers, depending on the manoeuvre speed requirements. The function has been tested with sun sensors to detect eclipse and to rotate so that solar rays impact the photovoltaic cells and not on the optic communication system, in order to prevent saturation. The system's node connectivity, possible states and phases are further explained in [6] and [7].

3.3. Inter-Process Communication

Once all the required modifications have been set for the use of the programme, it has been proceeded to analyse, modify and test Inter-Process Communication (IPC) capabilities. When hardware prototypes are tested on the air-bearing test bench [8], the satellite will not translate within the Global Navigation Satellite System (GNSS). Therefore, the IPC mechanism is required to use the position computed within 42 so that the simulation can be tested in a real-case scenario.

Regarding the whole emulator, 42 will be responsible for providing the orbit simulation variables. At the same time, other tasks will be delegated to external software for ACS and mission control, or to hardware sensors and actuators connected with the onboard CubeSat computer.

The system architecture comprises a leading 42 simulator, which interacts with the dependencies, N external standalone attitude control bidirectional applications, and an external 42 simulator that receives data and acts as a Graphical User Interface (GUI). Each external application simulates an individual CubeSat system. Figure 3 illustrates the system's architecture with two satellites:

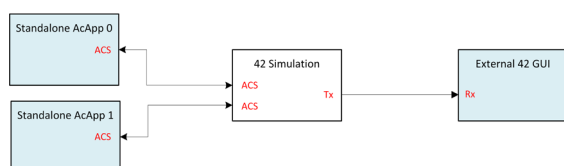


Figure 3. IPC system architecture

Each block can be located on a different device or combine several features on one computer. For the PLATHON project, the 42 Simulation and the Standalone ACS apps are based on the same server, while the graphical representation is in an external machine. However, everything can be controlled remotely from a unique device using Secure Shell Protocol (SSH) for convenience.

3.4. Post-processing

With all the available data saved into document files, a highly customisable MATLAB code

extracts the formatted outputs and saves them into body-indexed matrices.

A 3D representation using Simulink has been designed based on MATLAB's Aerospace Toolbox for a limited number of satellites. The purpose of the model is to visually analyse attitude changes of 42 simulations, which can be saved into a high-speed video file.

As a result, it is unnecessary to rerun a previous simulation to view satellite manoeuvres. This saves computational time and allows the user to select a narrow interval of time at a specific simulation speed.

The required data comes from 42 output files except for the quaternions in the Earth-centred, Earth-fixed (ECEF) frame, as the programme only saves them in the Earth-centred inertial (ECI) frame. However, this approach was not designed for an expandable number of bodies. Thus, the visualisation of constellations is constrained to a low number of spacecraft, which is sufficient to validate the results among constellation subgroups or clusters.

4. Results and discussion

4.1. Constellation generation

Once the programme had been modified to fulfil the project's initial requirements, it was then tested and validated with custom design constellations, and currently operative ones such as Iridium NEXT, shown in Figures 4 and 5. This constellation covers the entire Earth with 66 active devices while another nine remain as a backup. This example was chosen because of its design in which each satellite is linked to the four closest satellites, enabling independent service from any local ground infrastructure.

Figure 4 illustrates the 3D Camera view at a particular time on 14 June 2021. The GUI allows for movement between satellites and shows local and global axes.

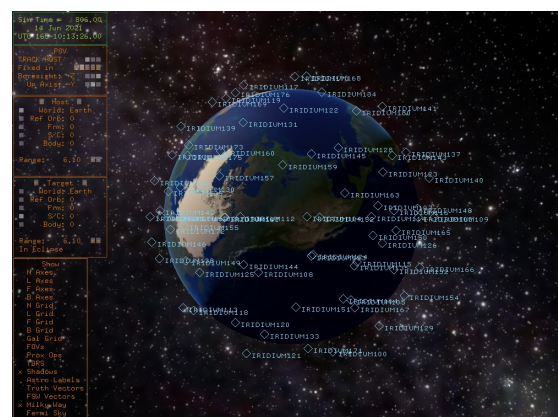


Figure 4. Iridium NEXT. 3D Camera View

At the same time instant, the 2D map view of Figure 5 shows each satellite's position, current orbit, and field of view towards nadir.

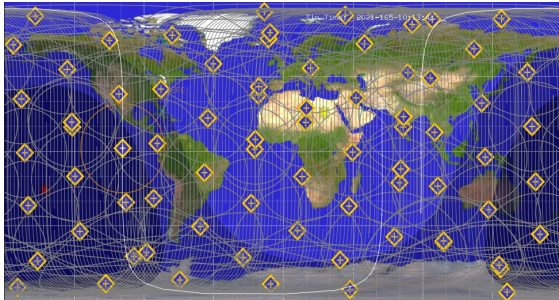


Figure 5. Iridium NEXT. 2D Map View

4.2. IPC and ACS manoeuvres

Regarding Inter-Process Communication, the current ACS app modification allows changing Euler angles at a specific time to simulate that two CubeSats rotate to point to each other and send data through optical communications.

This simulation serves as a demonstration of the IPC capabilities and as a proof of concept for the future PLATHON project architecture. It paves the way to a more elaborate simulation that recreates a full-on constellation when assembled with the cFS and NS3's node connectivity features currently under development.

Figure 6 represents two CubeSats orbiting in formation with their main body axis visible:

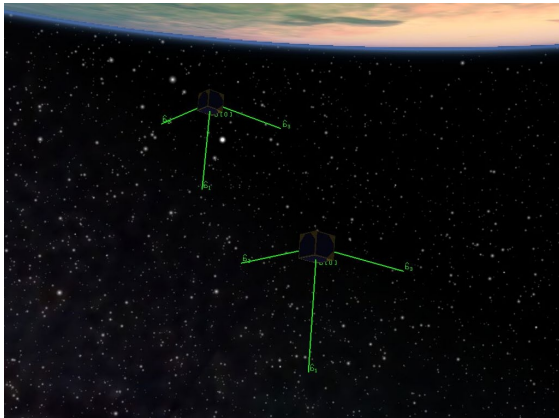


Figure 6. IPC Architecture – Initial attitude

At a specific time, both satellites receive a telecommand from their respective ACS applications to point to each other. The result is shown in Figure 7.



Figure 7. IPC Architecture – Modified attitude

The attitude modifications necessary to perform the rotations have been externally controlled from the main simulation. Each satellite takes into consideration the relative position of the other, and computes the rotations independently.

The visualisation is also being externally provided by another machine running 42 and relaying the data. The receiving device only represents the data as it comes through the socket interface.

4.3. MATLAB GUI

The MATLAB GUI offers an alternative approach that requires extensively less computational power, both in terms of CPU and GPU, once the results have been recorded.

Figure 8 shows the post-processing of the IPC architecture during the satellite pointing manoeuvre with Simulink 3D Animation.

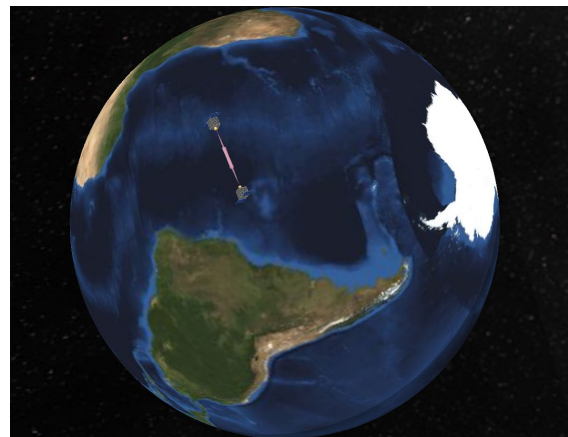


Figure 8. Simulink 3D Animation – IPC mode [9]

5. Conclusions

The PLATHON project has selected 42 as the main propagator due to its connectivity with all the OpenSatKit modules. After analysing the whole system architecture, the connectivity between the programmes has been deemed feasible for the emulation of CubeSat constellation missions involving laser-based inter-satellite communication and ground-to-satellite links.

The pre-processing of input files has been automated to design custom constellations and download data from orbiting ones.

42 has been customised to PLATHON's mission, and it has been modified to be connected to the Inter-Process Communication network currently under development.

The post-processing of output files has been automated and combined with MATLAB features to save computational time and allow the user more manoeuvrability.

The results have paved the way for SiTL simulations, providing a basis for the subsequent software connections and hardware implementations, which may be performed in the following years to reach the next mission validation level with a complete HiTL emulation.

5.1. Future prospects

The PLATHON project requires extensive efforts to reach a fully functional, stable status.

42 propagator perturbation models, although precise for these analyses, will require more complexity to provide better approximations and higher accuracy during long simulations.

Similarly, the current 42 models for both sensors and actuators might be too simple to portray the fluctuating space environment. Considering that the GNSS position will be the only 42-dependant asset during the HiTL emulations, the model should be enhanced. The other sensors and actuators will be included within hardware connections.

Finally, integrating all the OpenSatKit modules through the IPC will be the logical step forward, principally combining the cFS with 42 and then with COSMOS.

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