Simulation of CubeSat on-board computer system operating modes using MATLAB

Jesus Tapia(1), **Jhasmin Huillca**(2), **Omar Blas**(3), **Haile Abad**(4)
(1) Universidad Nacional de Ingeniería, +51 976485545, jtapiag@uni.pe
(2) Universidad Nacional de Ingeniería, +51 932698715, jhuillcaa@uni.pe
(3) Universidad Nacional de Ingeniería, +51 989546590, oblasm@uni.pe
(4) Universidad Nacional de Ingeniería, +51 931 274 097, john.abad.a@uni.pe

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A fundamental part of a nanosatellite is its control subsystem and on-board computer (OBC) whose functions are to receive and transmit commands, provide data storage, execute the commands and ensure the good state of the nanosatellite. It is therefore important to perform as many tests and simulations as possible, in that sense a simulation of the different operating modes of a Cubesat during a period of 24 hours using state machines in Stateflow has been developed. For this purpose, data from the CubeDesign 2021 competition (organized by the National Institute for Space Research of Brazil-INPE) have been used, and the robustness of our system has been achieved by considering the largest number of possible scenarios, since a failure would be fatal for the mission. All this work is framed in the development of a future nanosatellite that aims to follow in the footsteps of CHASQUI I (CubeSat created in the facilities of the National University of Engineering and launched into space in 2014). The MATLAB simulation platform and its control logic tool StateFlow have been used for this work.

1. Introduction

At present, the development of Cubesat nanosatellites is in a continuous evolution, its fundamental structure is 1U (standard dimension of 10x10x10cm) with a mass ranging from 1 to 1.33 kg. In the academic and research fields, its study has increased in recent years, proving to be an important tool for the introduction of aerospace technology. In this context, the National Institute for Space Research of Brazil (INPE) organized the Virtual CubeDesign 2021 competition, whose objective was that the teams were able to develop modeling and simulation activities of space systems, fundamental for the analysis of a space mission.

For the development of the challenge, the Simulink/Stateflow tool was used to model and simulate the behavior of the OBC, the input data for this challenge were provided by the organizing committee, three important factors were considered when modelling the simulation, which were the simulation step, the total simulation time and the mode of operation.

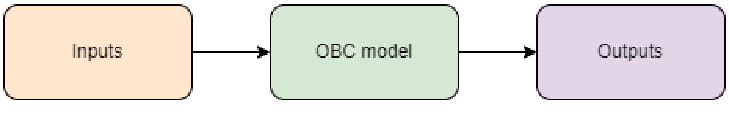

Figure 1: System overview.

Figure 1 shows a summary of the work performed, being the inputs the data provided by the organizer (battery status, latitude, longitude, etc) and requiring the output in the form of graphs and tables (battery voltage, visibility, operating modes achieved, etc). Among the main limitations of the work are that the simulation will be carried out at subsystem level and does not consider all aspects at component level, also the challenge considers hypothetical situations. Therefore, in a real mission, it is necessary to adapt some approaches so that the model and, consequently, the simulation result is faithful to the mission requirement [1].

To better understand the challenge and the information management subsystem, it is necessary to mention some important concepts.

- **State machines** They are a method that allows us to model a wide variety of systems whose outputs depend on the history of inputs and not only on their current value, in addition, certain Boolean conditions must be met to pass from one state to another (see figure 2).

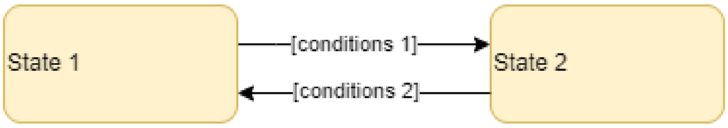

Figure 2: **Two-state system.**

- **On-Board Computer.** The on-board computer, commonly known by the acronym OBC (On Board Computer), is the brain of the satellite or spacecraft. It determines the satellite's mode of operation, communicates with each of the subsystems and is responsible for transferring information. Another of its functions is the response to the telecommands sent from the ground station, as well as the supervision of space missions, etc. It also includes autonomous failure management functionalities to ensure that the spacecraft can automatically recover from major anomalies and enter a safe state without the interaction of ground operators, in case of an emergency. Figure 3 shows the general scheme adopted for the operation of Cubesat.

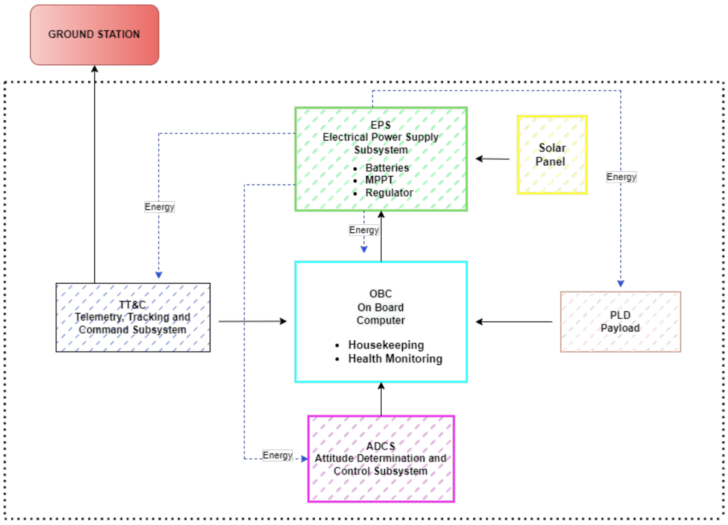

Figure 3: Schematic diagram of Cubesat operation.

In the work of Osman and Mohamed [2] performed a simulation of the OBC system and modes of operation in Proteus, they considered that this system had only two modes of operation (normal and interrupt), on the other hand, Rutwik Jain et al. [3] defined 12 operational modes for the satellite with a hyperspectral camera as payload. In our work we have considered six operational modes and we will treat both the satellite and the OBC system operational modes indistinctly.

2. PROCEDURE

2.1. Modes of operation

The OBC operates in different modes of operation that determine the tasks that it must perform at any given time. According to the regulations provided by the INPE, the following modes of operation that can be achieved by the CUBESAT during the mission must be considered.

Off, is the state where the OBC is completely switched off, this state is also reached due to the lack of power supply from the EPS or by Hard Reset remote control. When designing Stateflow, we chose to define this state as a default state, and it can also be reached from any other operating mode.

Boot, is the start state of the OBC software, this state is reached after the power supply that the OBC receives from the EPS, this power supply must exceed a certain threshold voltage (system minimum). We have as an output condition that this state must occur immediately after the identification of the deployed state.

Deployment, in this state the antennas are deployed, the exit from this mode of operation occurs after 10 unsuccessful attempts.

Safe is the operational satellite state and is reached in three situations: when a failure occurs in the nominal and transmitting state, after completion of the deployment state and by telecommand. It can only be exited by means of a valid telecommand.

Nominal, the main operating state that can only be switched to the safe state in the event of a system failure.

Transmitting is the transmission of information obtained by sensors or cameras. It is reached when the ground station is visible or, failing that, by telecommand. Visibility shall be defined by the range of the earth station by taking the longitude and latitude data; if it is not within the range, it shall be set to the nominal state.

In order to plot the states reached, the notation in Table 1 will be considered.

Table 1: Operational modes.

#	Modo de Operación
0	Off
1	Boot
2	Deployment
3	Safe
4	Nominal
5	Transmitting

2.2. Telecommands

Within the behavioral system of the OBC, received telecommands have higher priority and will change the operating mode of the system regardless of autonomous operation.

The telecommands defined in the work for the simulation are: ”hard reset”, ”soft reset”, ”nominal”, ”safe” and ”transmitting”. The ”hard reset” turns off the OBC system, while the ”soft reset” only represents a software startup. On the other hand, the ”nominal”, ”safe” and ”transmitting” telecommands set the operating mode to the state of the same name.

In the challenge we have considered it appropriate to facilitate the work by defining the telecommands as integers as shown in Table 2, in a real situation it would be implemented as an interrupt in which we would need to define priorities.

We have defined the telecommands in the MATLAB Workspace as a timeseries object so that a continuous reading of -1 indicates that no information is being received from the ground station, while a value from 0 to 4 allows us to enter a specific operation mode for the CubeSat.

3. Result

In the figure 4 we observe the general architecture, the telecommand and visibility variables use the latitude and longitude information to indicate if it is possible to send data to the ground station. The parameter that defines the transition from ”Off” to ”Boot” mode is the battery voltage, using as reference [4] we define that $V_{battery} > 3.3V$

Table 2: List of telecommands used.

Telecomando	Operation Mode
-1	No actions
0	Hard Reset
1	Soft Reset
2	Nominal
3	Safe
4	Transmitting

must be satisfied for the transition to occur. In the ”Boot” mode, the processor initialization must be performed in order to start the Real Time Operative System (RTOS) and the software layer [5]. Once the antenna is deployed, the transition to the ”Safe” state takes place.

In the ”Safe” state, the attitude stabilization and energy generation will take place by means of the orientation of the solar panels. The change to another state is only done by remote control. In the figure 5 we see the design in StateFlow, the data processing and the graphs are obtained in a Matlab script (.m file). For the simulation in Simulink, steps of 5 seconds have been considered, being the total time of one day (86400 s).

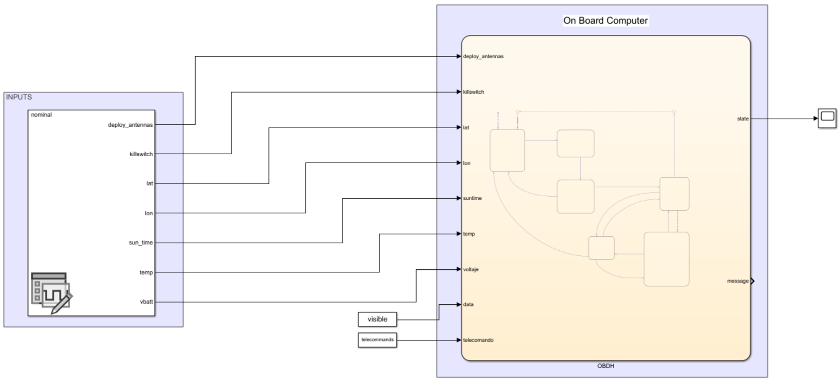

Figure 4: **General view in Simulink.**

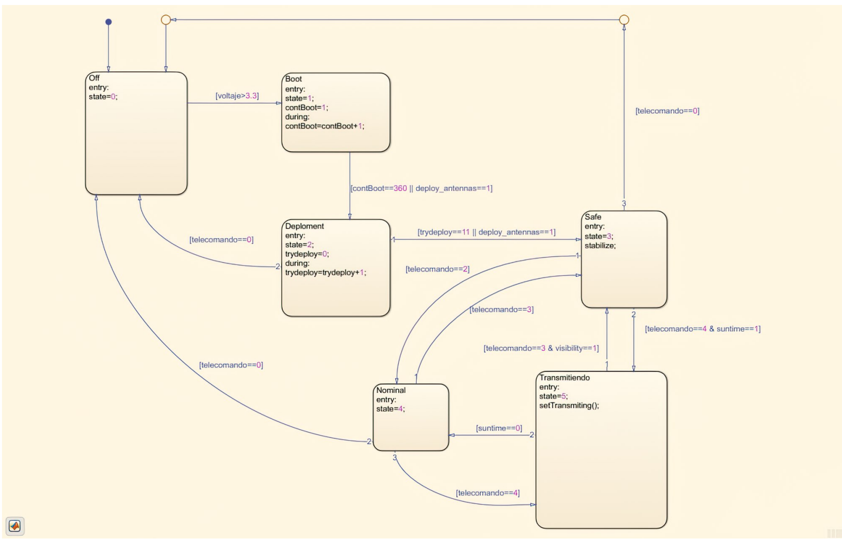

Figure 5: **Model in Stateflow.**

In the figure 6 we observe the battery voltage throughout the day, we notice that there are small variations (the maximum value is 8.5V and the minimum is 8.0795V) this is due to the pointing of the nanosatellite.For the power supply of the different subsystems a buck converter would have to be used since the operating voltages vary depending on the selected components and the payload, for example, in the case of the CubeSat OUFTI-1 they considered buses of 3.3V, 5V and 7.7V for the OBC1, OBC2 and communications subsystems respectively [6].

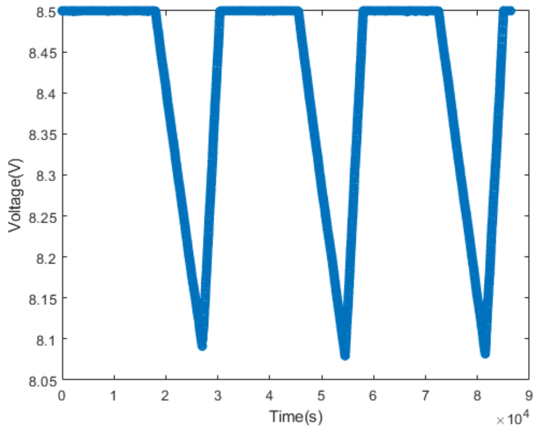

Figure 6: Battery voltage throughout the mission.

Using the data from the table 3 we can calculate the visibility time of the ground station, in the figure 7 we can see the trajectory of the nanosatellite and the position of the station (it has been considered that it is located in the facilities of the National University of Engineering). The figure 8 shows the interval in which the satellite can send data to the ground.

Table 3: Characteristics of the orbit.

Parameter	Value
Altitude	350km
Inclination	$97.55756°$
Semi-major axis	6927 km
eccentricity	2.06×10^{-3}

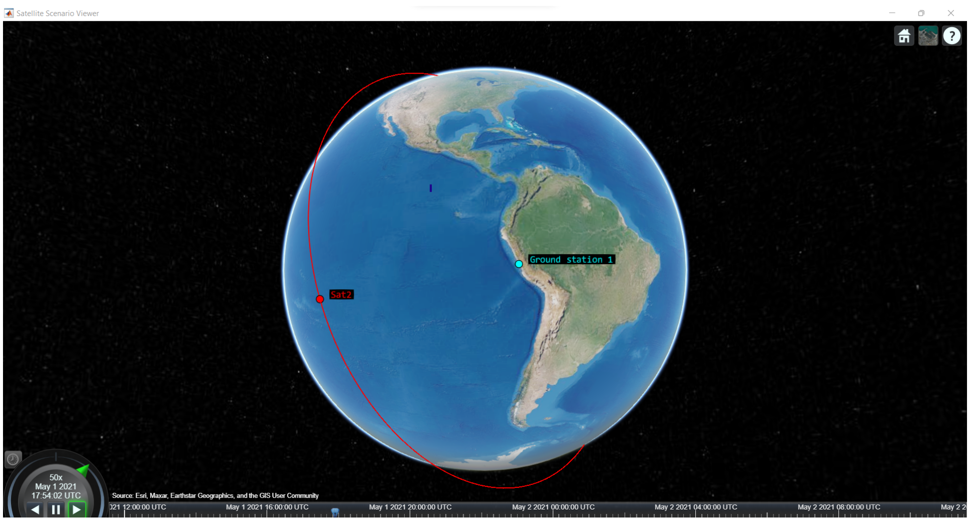

Figure 7: Trajectory of the nanosatellite.

Source	Target	IntervalNumber	StartTime	EndTime	Duration
"Sat2"	"Ground station 1"	1	01-May-2021 13:08:00	01-May-2021 13:11:00	180
"Sat2"	"Ground station 1"	2	01-May-2021 14:38:00	01-May-2021 14:49:00	660
"Sat2"	"Ground station 1"	3	02-May-2021 01:09:00	02-May-2021 01:17:00	480
"Sat2"	"Ground station 1"	4	02-May-2021 02:42:00	02-May-2021 02:53:00	660

Figure 8: Visibility of the ground station.

Finally, figure 9 shows the states reached during the mission in one day.

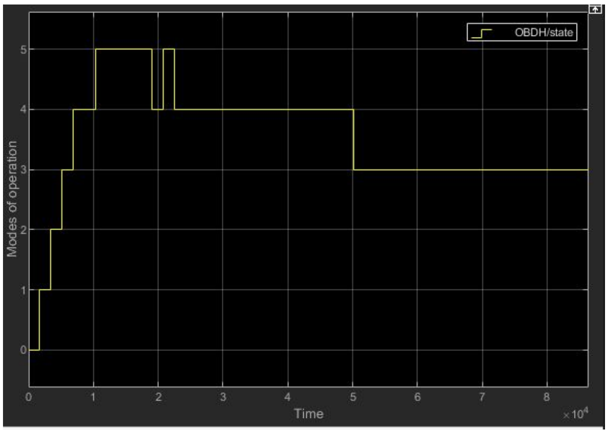

Figure 9: Operating modes achieved during the simulation according to the table 1.

4. Conclusion

The behavior of the on-board computer was modeled and simulated over a 24-hour period using state machines, also the visibility times of the ground station and the CubeSat trajectory were successfully calculated and plotted.

The development of the OBC CubeDesign challenge was essential for the members of the CHASQUI II group (Cubesat under development at the National University of Engineering facilities) to be able to understand the functioning and operation modes of the on-board computer.

As future research, it is proposed to extend the present work to include the simulation using Proteus, where the programming of the microcontroller and the reception of data from the rest of the subsystems would be more realistic.

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