Design and simulation of a model to determine the attitude and control the orientation of a nanosatellite for the CubeDesign contest

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In this document, a model is developed to determine and control the orientation of a nanosatellite whose properties are initial values provided by the CubeDesign 2021 contest. First, a sequence was elaborated in Stateflow for the nanosatellite to activate the modes according to defined input parameters. Then, for the attitude determination, a TRIAD optimization algorithm was implemented with the values given by the sun sensor and the magnetometer. The reference model of the control system was modified so that the nanosatellite can track the NADIR point and, at the same time, keep the speed of the reaction wheels within an acceptable range. The results show that all the objectives of the contest were achieved, so the simulated nanosatellite stabilizes while in orbit.

1. Introduction

CubeSats are small satellites that have been used in low Earth orbit by commercial companies and mostly educational institutions. These satellites are conducive to carrying scientific research and technology demonstrations in space in a costeffective and relatively easy to perform manner. However, the specifications and characteristics of a cubesat-type nanosatellite restrict the development of its subsystems, in this case the study will focus on the Attitude determination control system. The main objective of this subsystem is to control the angular velocities and the gradual orientation of the satellite in the desired spatial direction, often this direction is the vector pointing towards the earth or nadir. So, ADCS system functions can be divided into attitude measurement, attitude determination and attitude control. The present report documents the work done in the CubeDesign 2021 competition. Only attitude determination and attitude control were developed in a simulator software. Three important parts were performed: the behavioral modeling using a state machine, the estimation of the pointing direction and the dynamic modeling with a velocity control [1].

2. State of art

A. Dynamic model of the ADCS sub-system

The equation for the conservation of angular momentum of a body is given by:

$$\dot{L} + \omega \times L = \tau_{ext}$$

Where L is the angular momentum of the body and τ_{ext} is the external torque. The magnitude of angular momentum in a system can only be changed by applying external torques.

A charateristic of rigid bodies is that their angular momentum depends on the angular velocity of the body. The matrix equation is given by:

$$L = J.\omega + Lr$$

Where J is the diagonal intertia matrix of positive definite shape within the principal axis and Lr is the angular momentum of the reaction wheels or gyroscope.

Finally, the vector equation representing the equations of conservation of angular momentum of a body is given by:

$$\dot{\omega} = J^{-1}[\tau_{ext} - \dot{Lr} - \omega \times (J \cdot \omega + Lr)]$$

3. System Description

A. Attitude Determination

The Simulink diagram given by the contest gives us as information the vectors from the sun sensor and the magnetometer. The four vectors are used to determine the quaternion of the CubeSat in ECI coordinates. Its attitude can be calculated with the Attitude Optimization Matrix from the optimized TRIAD algorithm. For this purpose, the following steps are followed [2]:

TRIAD-I Algorithm:

$$r_1 = \frac{w_1}{|w_1|} \qquad r_2 = \frac{r_1 \times w_2}{|r_1 \times w_2|} \qquad r_3 = r_1 \times r_2$$

$$s_1 = \frac{v_1}{|v_1|} \qquad s_2 = \frac{s_1 \times v_2}{|s_1 \times v_2|} \qquad s_3 = s_1 \times s_2$$

The matrix A1 is expressed as:

$$A_1 = r_1 \cdot s_1^T + r_2 \cdot s_2^T + r_3 \cdot s_3^T$$

TRIAD-II Algorithm:

$$r_5 = \frac{w_2}{|w_2|} \qquad r_2 = \frac{r_1 \times w_2}{|r_1 \times w_2|} \qquad r_4 = r_5 \times r_2$$

$$s_5 = \frac{v_2}{|v_2|} \qquad s_2 = \frac{s_1 \times v_2}{|s_1 \times v_2|} \qquad s_3 = s_1 \times s_2$$

The matrix A2 is expressed as:

$$A_2 = r_5 \cdot s_5^T + r_2 \cdot s_2^T + r_4 \cdot s_4^T$$

Finally, the Attitude Optimization Matrix is determined:

$$\hat{A}' = \frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2} A_1 + \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2} A_2$$

$$A = 0.5 \left[\hat{A}' + \left(\hat{A}'^{-1} \right)^T \right]$$

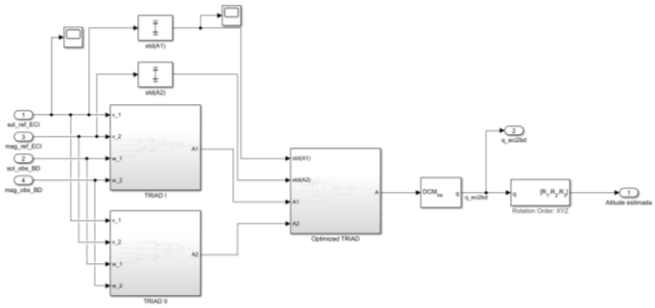

Figure 1: Diagram in Simulink to find the estimated attitude of the CubeSat using optimized TRIAD.

B. Orientation Control

Satellites normally must be pointed toward the Earth for communication missions. Therefore, the CubeSat must rotate around a vector that points towards the earth. For the contest, the vector is required to point towards the NADIR point, which is the intersection between the vertical of the observer and the celestial body. These equations are implemented in Simulink and simulated to obtain the attitude of the CubeSat in the LVLH coordinate system [3].

$$o_{3I} = -\frac{r_I}{\|r_I\|}$$

$$o_{2I} = -\frac{r_I \times v_I}{\|r_I \times v_I\|}$$

$$o_{1I} = o_{2I} \times o_{3I}$$

$$A_{IO} = [o_{1I} \quad o_{2I} \quad o_{3I}]$$

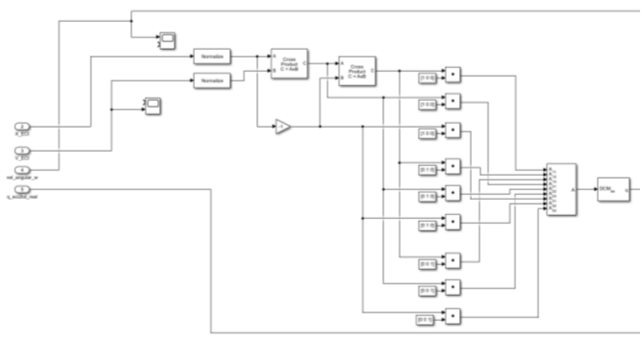

Figure 2: Simulink diagram to determine the quaternion in LVLH coordinates.

This orientation vector is used as a reference for angular position control. However, this only applies if the CubeSat is in stabilization mode. For this reason, a “Step” block was added to the diagram, which represents a signal that indicates that the ADCS system must go to stabilization mode. In this mode, the position control is activated and the CubeSat will point to the NADIR point while the angular rate controller tries to keep this variable at a value equal to zero. The outputs of both controllers are added together and serve as the torque input for the CubeSat's reaction wheel system, according to the following equation [4]:

$$L = -k_p \delta q_{1:3} - k_d \omega$$

where L is the required torque for the reaction wheels, k_p and k_d are positive scalar gains, δq is the error quaternion and ω is the angular velocity of the CubeSat.

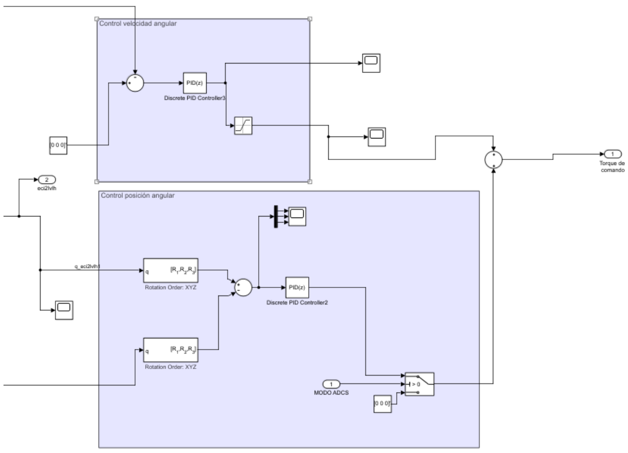

Figure 3: Simulink diagram for CubeSat position and angular velocity control.

C. Behavioral Model

The finite state machine ADCS system consists of 5 operating modes: Safety, Calibration, Pointing, IDLE (Initial) and Detumbling. These modes were extracted from the CubeDesign 2021 competition rules. The variables or inputs that affected the change of state of the subsystem are the angular velocity, orbit propagator, orientation determination, pointing error, the presence of the sun, the state of the reaction wheels and the telecommands that had the highest priority. The five modes of operation will be described below.

The IDLE mode is the nominal mode of the cubesat after launch. In addition, it is used when the cubesat in stable mode (angular velocity less than 1 rad/s) enters eclipse; at the same time, the orbit propagator, the orientation determination and the reaction wheels must be operational.

The pointing mode is used when the cubesat is exposed to sunlight. Like the IDLE mode, the cubesat must be stabilized; in addition, the orbit propagator, the orientation determination and the reaction wheels must be operational.

The safety mode is used immediately when the orbit propagator or the orientation determination is not operational. Other critical cases are when the calibration is unsuccessful, the reaction wheels fail to come out of saturation, the pointing error is out of the allowed range or the CubeSat angular velocity cannot be reduced.

The calibration mode is used in order to point the camera to the Sun after 100 seconds from the start of the simulation and remain in this mode until the calibration is successfully completed. If after a set time the calibration is not successful, the subsystem switches to safety mode.

Finally, the CubeSat will be in detumbling mode when the angular velocity passes the set limits. Additionally, the orbit propagator and orientation determination, as well as the reaction wheels, must be operational.

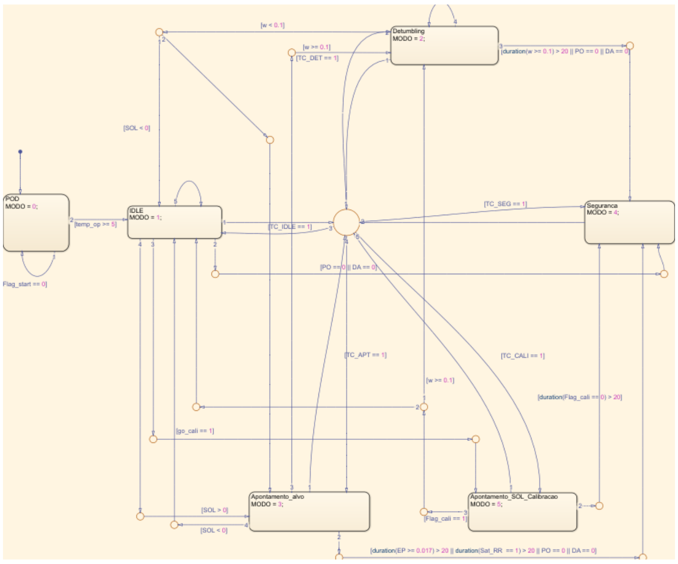

Figure 4: State Flow of compartmental design in Simulink.

4. Results

The CubeSat simulation starts with the ADCS subsystem disabled. When t = 10s, the stabilization mode is activated, and therefore the speed control is activated (see Fig. 5). The initial angular velocity of the CubeSat is [0.006 0.006 0.006] (rad/s). In a time of approximately 57s, the CubeSat stabilizes and maintains its angular velocity at zero. Then, at t = 350s, the CubeSat's pointing mode is activated, so position control is activated without deactivating velocity control (see Fig. 6). In this mode, the CubeSat tries to point towards the NADIR point while keeping its angular velocity close to zero. It is observed that, in a time of 200 seconds, the CubeSat manages to point to NADIR with pointing error values shown in the table.

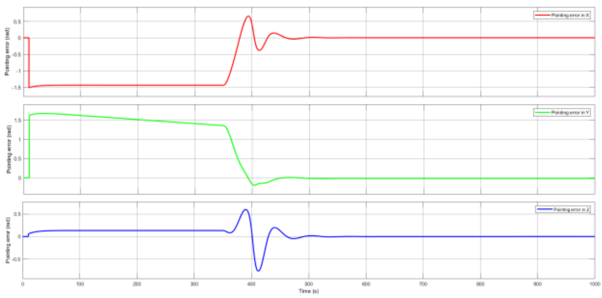

Figure 5: Pointing error of the CubeSat in X, Y and Z

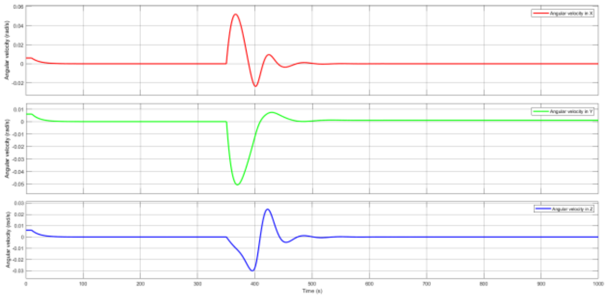

Figure 6: Angular velocity of the CubeSat in X, Y and Z

Table 1. Pointing error values after settling time

Euler Angle	Pointing error (rad)
X	1.962×10^{-5}
Y	1.597×10^{-5}
Z	3.345×10^{-5}

5. Conclusions

In this document, a model is developed to determine and control the orientation of a nanosatellite whose properties and initial conditions are provided by the organizers of the CubeDesign 2021 contest. The tests carried out with the ADCS system model for the CubeSat operating modes were satisfactory, since the nanosatellite activates the modes correctly according to the input parameters of the system. Likewise, it was possible for the CubeSat model to stabilize its angular velocity during the stabilization mode, and during the pointing mode, to point towards the NADIR point with pointing error values in the three axes within the allowed ranges. In future works, the CubeSat will be implemented and the technical data of its components will be introduced in the model to verify its operation before sending it into space.

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