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Electromechanical flight stabilization system for CubeSat nanosatellites

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Abstract
The objective of the research was to design and simulate a stabilization system for attitude control of CubeSat nanosatellites in LEO orbit. The electronic system was inside the mechanical system, designed in Proteus. The mechanical system was designed in SolidWorks, then a CubeSat 3U CAD was downloaded for simulation and finally, all CAD designs were assembled. These data were used for the analysis of the spatial environmental perturbations of aerodynamic drag, gradient, gravity and magnetic field. Attitude representation was done by analyzing the Euler, Poisson and Quaternions equations. Then, a fuzzy logic control was created with two cases for automatic control. The analysis and virtual reality simulation revealed the correct attitude control on the CubeSat 3U nanosatellite, considering the perturbations of the space environment and a new 25° orientation of each axis.

Keywords: fuzzy control; simulation; virtual reality; electromechanical stabilization system; LEO orbit.

Sistema electromecánico de estabilización de vuelo para nanosatélites CubeSat

Resumen
El objetivo de la investigación fue diseñar y simular un sistema de estabilización para el control de actitud de nanosatélites tipo CubeSat en la órbita LEO. El sistema electrónico estaba dentro del sistema mecánico, diseñado en Proteus. El sistema mecánico se diseñó en SolidWorks, luego se bajó un CubeSat 3U CAD para la simulación y finalmente, se ensamblaron todos los diseños CAD. Estos datos se utilizaron para el análisis de las perturbaciones ambientales espaciales de arrastre aerodinámico, gradiente, campo gravitatorio y magnético. La representación de la actitud se hizo mediante el análisis de las ecuaciones de Euler, Poisson y Quaternions. A continuación, se creó un control de lógica difusa con dos casos para el control automático. El análisis y la simulación de realidad virtual revelaron el correcto control de actitud en el nanosatélite CubeSat 3U, considerando las perturbaciones del entorno espacial y una nueva orientación de 25° de cada eje.

Palabras clave: control difuso; simulación; realidad virtual; sistema electromecánico de estabilización; órbita LEO.

1 Introduction

The satellite is a natural or artificial object which turn around a planet on a specific orbit. The artificial satellites are vehicles, would was manned or unmanned, they transport and retransmit information [1,2]. Many satellites orbit the earth, they provide us of instant communication, internet or television signal, GPS signals and the most advanced satellites provide us of weather conditions of Earth [3,4].

Since putting a satellite into orbit has been very expensive, the nanosatellites have been an alternative because they are unmanned vehicles, without much weight, size, and cost [5,6].

There are many types of nanosatellites such us CubeSat, generally these are putting into orbit LEO (Low Earth Orbit), and the characteristics like weight and useful load are defined depending on the mission [7]. The development of nanosatellites is a trend in space science and research engineering area because they enable the study of nanosatellites subsystems and new technologies. The CubeSats are an example of the maximum use of electronic systems and technological advances [8]. Therefore, a lot of universities around the word, work with these nanosatellites.

A large part of CubeSat's tasks needs and excellent

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attitude control because much of the tasks performed by nanosatellites in space require precise guidance and accuracy (attitude) to meet mission objectives; considering that the constructional characteristics such as total mass and power of nanosatellites are limited and many of them lack attitude control systems [9].

The nanosatellites have a wide range of attitude control systems. Some control systems have 3-axis magnetometers and 3-axis gyroscopes to measure relative rotations to determine absolute orientation [10], others incorporate sun sensors, star sensors or GPS to measure rotational speed [11].

For the change of orientation, the actuators are the components that produce the necessary torques to achieve the desired attitude, among the most used are, reaction wheels, torsion bars and thrusters [12], but the most accurate actuators are the reaction wheels, these respond to external disturbances that are present around the nanosatellite, generating corrective torques to change the angular acceleration.

An actuator alternative is the BLDC (Brushless Direct Current) brushless DC motor, where an electronic controller replaces the brushes, thus improving the reliability of the motor.

To achieve attitude control of a nanosatellite in the three axes (x, y, z), at least three reaction wheels, placed in three directions in different typologies, are necessary [13].

The present work consists of the design and simulation of a stabilization system to control the rotation and orientation of a CubeSat type nanosatellite.

It is designed and tested the operation of the subsystems: mechanical, electronic and control of the stabilization system considering the earth's gravity and the conditions in the low LEO orbit.

2 Methodology

For the development of the work, the V methodology was used, applied to the development of mechatronic devices, through which the functional requirements of the system were determined, such as system measurements, maximum weight allowed, type of material for the structure, type of working orbit of the nanosatellite, speed of rotation about the center of masses, angle of inclination, altitude, among others.

2.1 Conceptual design

A cubic carbon fiber structure was designed to support and protect the components. The motors are controlled by a PIC microcontroller, to which the MPU6050 sensor signals are input, consisting of a gyroscope and accelerometer; the sensor takes simulated data from a space environment in LEO orbit. The power supply is responsible for the power supply for the operation of the entire stabilization system.

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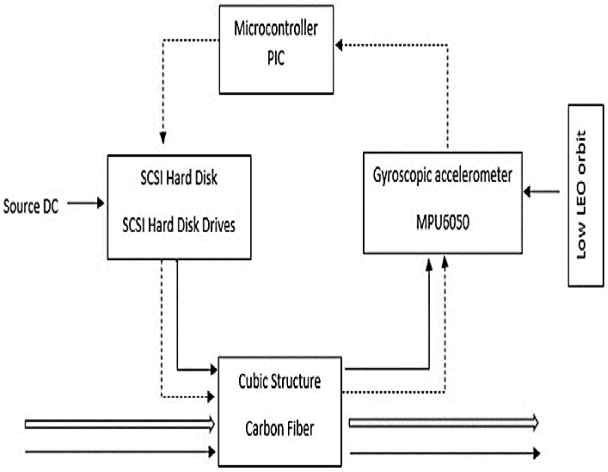

Figure 1. Conceptual design of the stabilizer system structure.
Source: the authors

In the Fig. 2 shows the flowchart of the simulation of the stabilizer system for a nanosatellite, where the MATLAB program collects information from other software packages such as SolidWorks and Proteus, then by means of VR Sink it is possible to simulate the behavior of the system in virtual reality.

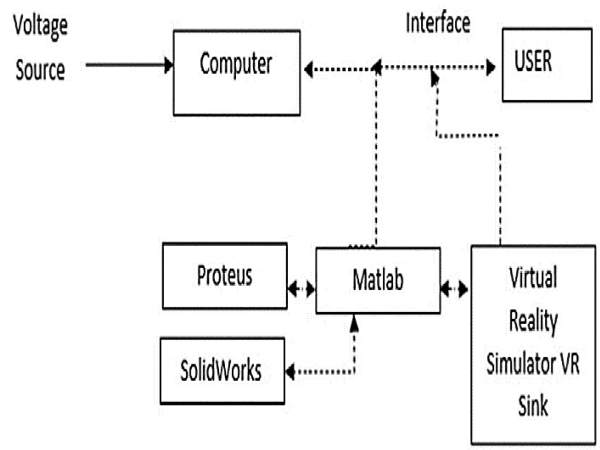

Figure 2. Simulation diagram of the stabilizer system.
Source: the authors

2.2 Mechanical design

To achieve control in the three axes of the CubeSat type nanosatellite, four reaction wheels were installed, one in the "x" axis, one in the "z" axis and two in the "y" axis; these motors have the capacity to rotate the nanosatellite around the axis of its center of mass, since they have flywheels that cause the acceleration of the rest of the satellite in the opposite way to the rotation.

For the selection of the material for the structure, different materials used in the aerospace industry were analyzed, after which carbon fiber was chosen because it has properties such as: high resistance, low weight, flexibility, tolerance to high temperatures and low thermal expansion.

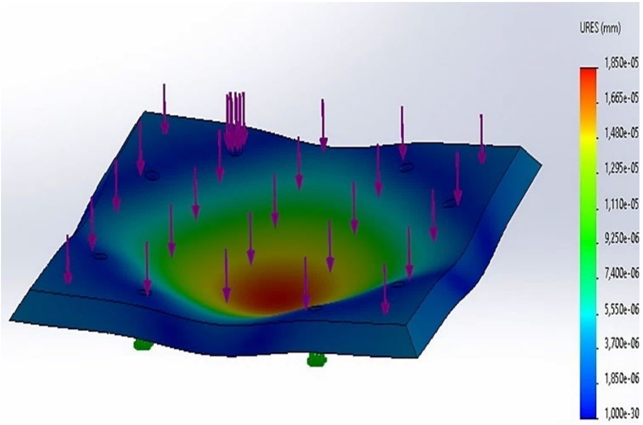

Figure 3. Base plate deformation analysis.
Source: the authors

The analysis of deflection and deformation forces to which each carbon fiber plate of the structure will be subjected was carried out, considering a thickness of 3 mm, y 8x8 cm^2 area; for the base plate it was considered that it must also support the weight of the control system, and for the side and top plates the analysis was performed considering the weight of each actuator (Fig. 3).

2.3 Electronic design

The control system board is made of 78x78 mm^2 and consists of a PDB-XT60 power regulation board, a MPU6050 sensor, a PIC16F877A microcontroller and the actuator controllers. For the PCB board design, the track size was calculated based on the IPC-2221 standards, obtaining a track width of 0,146 mm Fig. 4.

In space applications it is essential to eliminate all types of mechanical contacts such as bearings, gears, and motor brushes, for this reason we used BLDC motors of the ATA hard disk type (Fig. 5), which stand out for their torque characteristics, wide speed range (7200 a 8000 rpm), and unsurpassed service life. Fig. 6 shows the assembled stabilization system, with all components, mechanical and electronic.

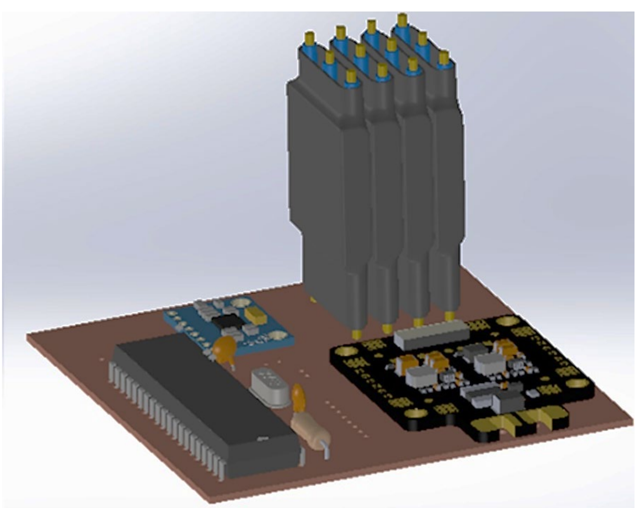

Figure 4. Electronic system exported to SolidWorks.
Source: the authors

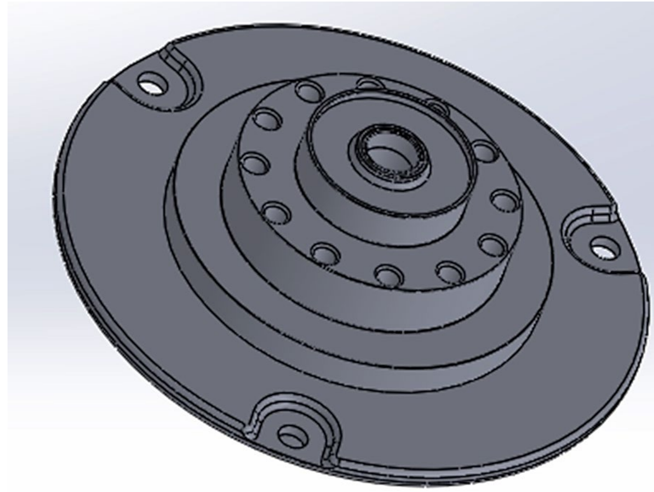

Figure 5. Hard disk motor.
Source: the authors

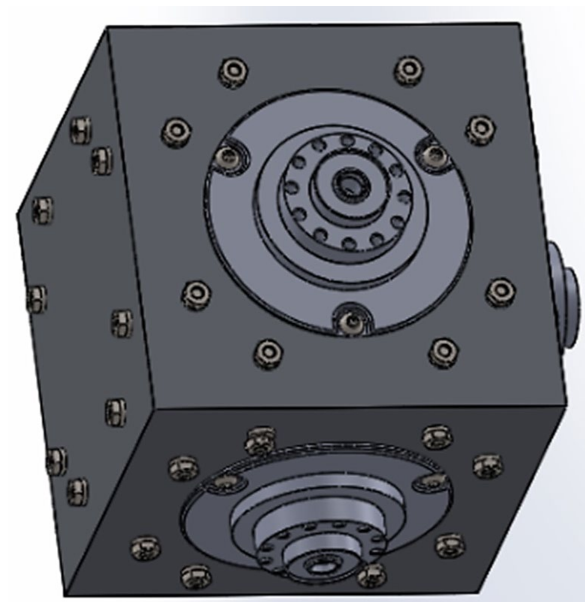

Figure 6. Mechanical stabilization system.
Source: the authors

To make the attitude control system of the nanosatellite we considered the motion of celestial bodies and laws of orbital motion, considering some elements such as: Eccentricity, Inclination, Altitude, Orbital velocity and the shape and physical characteristics of the nanosatellite. Their values were calculated with respect to locations of UTE nanosatellite previously sent to space (Table 1.).

Table 1.
Orbit elements.

Orbit elements	Value
Eccentricity	e=0
Inclination	i=90°
Altitude	h=629 km
Orbital velocity	V=27169.20 km/h

Source: the authors

Table 2.
Disturbances at 620 km of altitude.

Disturbance	Value [Nm]
Gravitational Gradient	3.117×10^{-10}
Magnetic Fields	4.645×10^{-7}
Atmospheric Drag	8.572×10^{-11}
Solar Radiation	0

Source: the authors

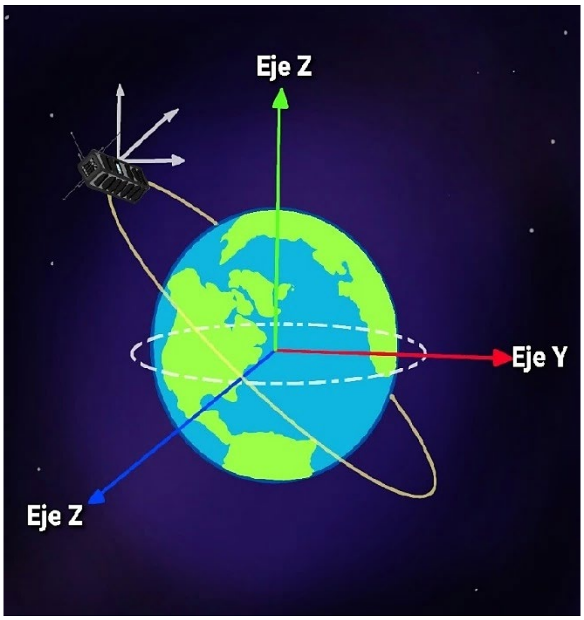

Figure 7. Reference systems.
Source: the authors

In the space environment there are disturbances to which the CubeSat is subjected, and which affect its orbit and attitude, among the disturbances considered are: aerodynamic drag, gravitational gradient, magnetic field, and solar radiation [14], the latter is stronger at higher altitudes so in LEO orbits it has a negligible value and was not considered. Table 2 shows the calculations performed for the perturbations at an altitude of 620 km which will simulate the space environment.

The orientation of the nanosatellite is usually analyzed with respect to a reference system, as shown in Fig. 7, which can be expressed by means of director vectors or angles. For this case, the orientation was analyzed, and the attitude representation was performed using Euler, Poisson, and Quaternion kinematic equations, which will simulate the attitude of the nanosatellite.

2.3.1 Euler equations

The system analyzes the rotations performed around the principal axes, to which rotation angles are associated for the axes (x, y, z), by means of the angular velocities of the sensor [15]. This is represented in eq. (1).

$$\dot{\phi} = \begin{bmatrix} 1 & sin\,\Phi\ tan\,\Theta & cos\,\Theta\,tan\,\Theta \\ 0 & cos\,\Phi & -sin\,\Phi \\ 0 & sec\,\Phi\ \ sin\,\Phi & cos\,\Phi\ \ sec\,\Theta \end{bmatrix} \cdot \bar{\omega}_{b/v} \qquad (1)$$

2.3.2 Poisson equations

It is represented by the cosine direction matrix and takes the time of the rate of change as a function of (p, q, r) [16]. As seen in eq. (2).

$$\dot{c_{b/v}} = -\begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \cdot c_{b/v} \qquad (2)$$

2.3.3 Quaternions

It is obtained from the angles provided by the sensor, and the attitude representation is defined by the vector and the angle representing the twist [17]. It is defined in eq. (3).

$$Q = \begin{bmatrix} q_0 \\ q_1\hat{\imath} \\ q_2\hat{\jmath} \\ q_3\hat{k} \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{\delta}{2}\right) \\ V_{(x,y,z)}\ sin\left(\frac{\delta}{2}\right) \end{bmatrix} \qquad (3)$$

For testing and simulation purposes, the assembled stabilization system was exported to Simulink together with a standard CubeSat 3U design (t. 8). the assembled system reached a total weight of 3.808 kg.

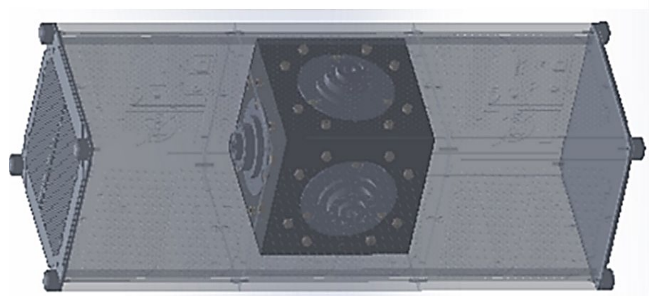

Figure 8. Stabilizer and CubeSat System Assembly.
Source: the authors

The automatic control system provided with a fuzzy controller and the simulation result using virtual reality elements are presented in Fig. 9.

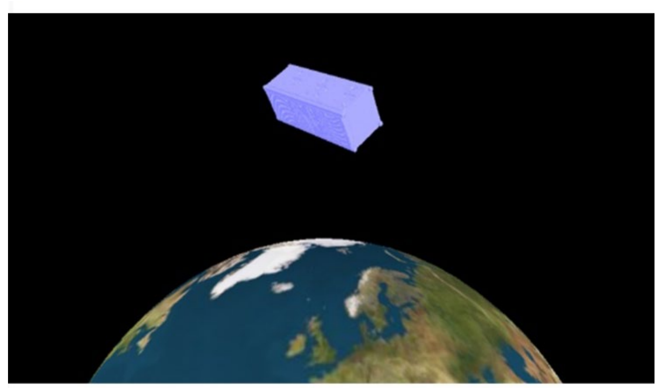

Figure 9. Virtual Reality Simulation.
Source: the authors

3 Results and discussion

In the Fig. 10 shows the design and control flowchart for a CubeSat type nanosatellite stabilization system.

The process started with the creation of the structure of the stabilizer system in the SolidWorks software, then a printed circuit board was designed in the Proteus software for the connections of the hard disk controllers and motors, the MPU6050 sensor, the PIC microcontroller, and other components.

The PCB design was exported in CAD format to SolidWorks software, to assemble the mechanical system and the electronic system of the stabilizer, for this purpose a fixed subassembly was made and, for the motors a flexible subassembly; then the assembled system was exported to MATLAB software and the project was saved in Simulink to test the operation of the motors.

To start with the tests in Simulink, a Gimbal Join was added which functioned as a sensor between the CubeSat 3U and the stabilizer system. Afterwards, several angular velocities were applied to the motors of the system and the working units were established in the connections, which generated a correct reading of the values of angular velocities, position, torque and acceleration of the nanosatellite; the turns and orientation change of the CubeSat were evaluated with the creation of a rotational kinematics subsystem using the Poisson, Quaternion and Euler equations, which established the most appropriate technique for the simulation and obtained a correct attitude representation.

A spatial perturbation subsystem was added, and two fuzzy control subsystems were created to evaluate the performance of the actuators; the first case: the stabilizer system performed a correct attitude control when the CubeSat was exposed to spatial perturbations, the second case: the stabilizer system performed a correct attitude control when the CubeSat was exposed to spatial perturbations and a new orientation of 25° for each axis. Finally, a Virtual Reality simulator was created, the results were sent, and the CubeSat 3U motion video was generated.

The CubeSat 3U and the stabilizer system have a total weight of 3.808 kg for the tests, an altitude of 620 km was determined, an orbital velocity of 27169.2 km h-1 and the perturbations calculated for each axis.

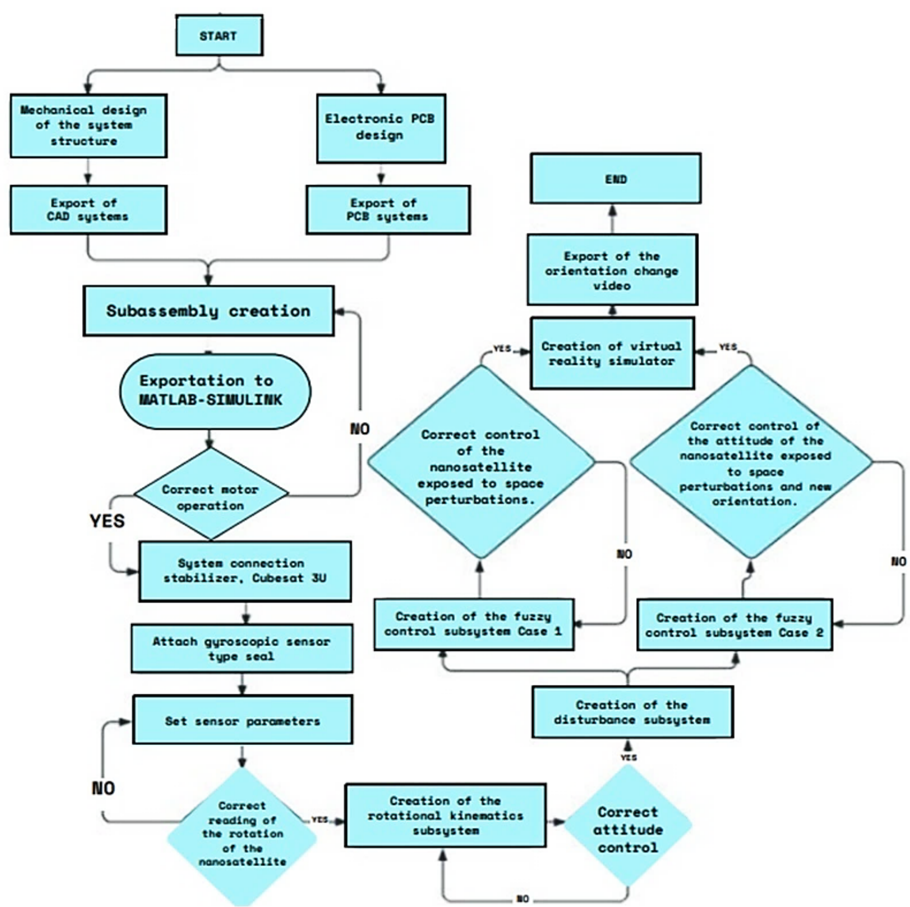

Figure 10. Flow diagram of the design and operation of the stabilizer system.
Source: the authors

Table 3.
Velocity and torque generated by the perturbations for each axis of the CubeSat.

Axis	Disturbance [Nm]	Disturbance [rpm]
X	-2.378×10^{-10}	0
Y	4.645×10^{-7}	0.516
Z	5.495×10^{-10}	0

Source: the authors

Table 4.
Velocity and touch generated by the stabilizer system for each CubeSat axis.

Axis	Torque [Nm].	Angular speed [rpm].
X	1.723×10^{-3}	0
Y	23.198×10^{-3}	21.43
Z	0.803×10^{-3}	0

Source: the authors

The maximum torque and maximum angular velocity provided to the nanosatellite by the environmental perturbations are shown in Table 3 below.

To test the stabilization system, the 4 motors were activated and an input from 0 to 8000 rpm was provided for each motor in the two directions of rotation, the maximum torque and maximum angular velocity provided to the nanosatellite, is observed in the following Table 4.

A fuzzy controller was developed, which receives information from the angles provided by the gyroscope, with which the operating ranges of inputs for control are defined. Two scenarios were created for the attitude control of the nanosatellite.

Case 1, the initial orientation was defined as the desired orientation at a rotation angle of 0° for each axis, and the perturbations were activated to evaluate the performance of the fuzzy control. At the start of the simulation the stabilizing system controlled the attitude and stabilized the nanosatellite at 0.03s, with an oscillation of 0.001˚.

Case 2, the desired orientation was defined with change of rotation angle from 0° a 25° for each axis of the nanosatellite and the environmental perturbations were activated. At the start of the simulation the stabilizer system controlled the attitude and stabilized the nanosatellite at 1.85s, with an oscillation of 0˚.

1 Conclusion

A stabilization system was designed for the attitude control of CubeSat 3U type nanosatellites, with a total weight of 0.808 kg, being the support structure a cube-shaped base of 80 mm on each side, with a thickness of 3 mm and carbon fiber material.

It was determined that "BLDC motor" type reaction wheels are the most accurate actuators for attitude control.

The arrangement of the wheels in the stabilizer system is, one for each axis (x, y, z) and an extra one on the y-axis, which provided a higher torque and angular velocity for the nanosatellite, with respect to the other axes.

The matrix of the Euler kinematic equations was evaluated and determine infinite values when the nanosatellite is directed from 90° a 270° (from top to bottom), this produced errors in the attitude reading; therefore, the Poisson and Quaternion equations are established as optimal for the attitude representation in simulation.

The fuzzy logic controller was accurate to validate the performance of the stabilizer system and performed a correct attitude control of the CubeSat 3U was exposed to spatial perturbations and different orientations.

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