Single Axis Control Using A Reaction Wheel In A Cubesat Manufactured With COTS Solutions

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***Resumen*—In modern satellites it is common to find reaction wheels to control them. Moreover, the communications of the satellite with its earth base are a fundamental pillar for the success of the missions of these satellites, being able to know their attitude and having the ability to send commands to manipulate the state of the satellite is essential in each mission. In this work, a cubesat-type satellite was designed and built where using a single axis reaction wheel to control, these being widely used in satellites for attitude control. In turn, communications to send commands and alter the attitude of the cubesat were through the use of Wi-Fi and the design of a web page that acts as a ground station and can work on both cell phones and computers. The satellite also has a camera from which a signal is received on the web page interface and commands can be sent to take photos and videos. The components used are COTS type such as esp32, espCAM, batteries, DC motor and 3D printing with PLA. Finally, tests were carried out and commands were successfully sent from the web page to the cubesat, causing it to successfully change its attitude in a precise way.**

***Palabras Claves*—Reaction wheel, control, attitude, COTS,**

1. Introduction

1.1. Attitude determination and control system

System in charge of the movement and/or spatial direction of the satellite and the knowledge of this data during the development of the mission. It is subdivided into two types of components or subsystems: Sensors, which allow the determination and knowledge of the position and orientation of the satellite; and the actuators, which allow the control of the variables, position and/or orientation of the satellite.

1.11. Sensors: Its choice and position represents a vital part of the mission to obtain precision in data measurement and guarantee the proper development of the mission. As technology advances and the proliferation and miniaturization of onboard computers progresses, increasingly smaller and more complex sensors have been developed, along with more robust algorithms, leading to greater precision in mission development. The most used sensors for cubesats are[1]:

1.11a. Solar sensor: They are sensors responsible for determining the position of the ship with respect to the sun. Generally the CSS or coarse sun sensor is used. These are made up of photoelectric cells that convert the energy of photons into electrical current and subsequently into a digital signal. Depending on the location of the sensor and the intensity of the energy captured, the angle at which the sun is located with respect to the sensor can be determined. Several solar sensors are usually combined, usually 2 per axis, to determine the spatial vector towards which the sun is located.

1.11b. Magnetometer: They are sensors that measure magnetic fields. They consist of wound coils that detect changing magnetic fields in the environment by changing the current in the coils. It provides data on both the magnetic field and its rate of change, which allows obtaining the Earth's magnetic field vector and the direction and rate of rotation of the ship. There are single-axis magnetometers up to multi-axis magnetometers.

1.11c. Gyros: They are sensors that measure the rate of angular change of the ship. They can use methods such as rotating plates to optical sensors, and can have one working axis as well as multiple axes. In some cases, they are packaged with a magnetometer and an accelerometer.

1.11d. Star trackers or cameras: They are optical sensors that provide the direction and rate of change in the direction of the ship's positioning vector. They collect images of the celestial field and, using comparative algorithms, calculate the positioning vector with respect to the known stellar field. Generally, they are the most accurate sensors to provide data to the attitude determination and control system.

Although other sensors can be found such as Earth horizon sensors, those mentioned above are the most used and known.

1.12. Actuators or attitude controllers:: Actuators or controllers allow the ship to be maneuvered or reoriented to a specific location in a specific reference frame. The algorithms used are composed of force and torque equations in which the specific mass of the ship, the center of gravity and the moment of inertia are required to be kept updated. The technologies used in cubesat attitude control are[1]:

1.12a. Reaction wheels:: They are the most common and their operation is based on the use of weighted wheels that rotate thanks to electric motors and create stored momentum.

The wheel's momentum is transferred to the body of the spacecraft by brakes that stop the wheel from moving, but produce torque on the structure. Generally, wheels are used on each of the 3 main axles of the ship. As a disadvantage, they can become saturated or reach a maximum limit that limits their action.

Oland and Schlandbusch [2] present the design of an attitude control system for cubesats based on reaction wheels, where the great possibility that cubesats have of maneuvering using reaction wheels is demonstrated through simulations. On the other hand, Manggala [3] shows a prototype of smaller, low-cost reaction wheels for 1U cubesats, which generate a torque of 0.74 mNm, a rotation speed of 5°/s and consume a voltage of 8V. Figure 1 shows the dimensions of this prototype system.

Figura 1: Prototype board for attitude control system with reaction wheels.

1.12b. Magnetocouples or torque bars: They are actuators that use the principle of magnetic dipole moments. A current is produced in a coil that generates a magnetic field inside the ship. This magnetic field interacts with the Earth's magnetic field and produces a torque necessary to rotate the ship. Magnetocouples are generally used in the direction of each of the 3 main axes. Although they use less energy, they take more time to generate a rotation in the ship.

1.12c. Jet control system: It uses a set of thrusters that accelerate a propellant stored in tanks to propel the ship in the opposite direction using the law of action-reaction. They are less used due to the complexity of their system, the excessive cost and the weight they occupy in the ship. The most used are cold gas thrusters, hot gas thrusters, resistojets, electrospray, electric and ion thrusters.

For example, King [4] states the design and operation of an attitude control system using electric thrusters. By comparing this system with a reaction wheel system in a 3U cubesat, it was concluded that the propulsion system managed to exceed the 0.007° precision of the reaction wheels, without compromising more space in the structure or weight of the this.

On the other hand, Timilsina [5] presents an attitude control system with electrospray propellants using ethyl ammonium nitrate. It was incorporated into a 1U cubesat system but was never fully tested.

1.2. On-board computer

The on-board computer is an arrangement of microprocessor, memory banks and interface chip that allow the connection and integration of the subsystems. boards are usually found integrated with the entire computer system. Among the main functions are the processing of attitude and control system data, telecommunications, telemetry provision, fault detection and recovery, among others. The figure 2 presents the main board options for use as an on-board computer in the mi[6].

2. Methodology

The Project had 3 main phases developed in the aerospace engineering laboratory, which were: research, development and testing. In the first phase, a state of the art of similar projects was carried out, through which it was possible to determine the scope of the project, limit the use of a single axis for attitude control and be able to send commands and obtain information from the camera. For the transmission of data to and from the cubesat, it was decided to use the Wi-Fi technology integrated in the ESP module, since it additionally allowed the reception of the data provided by the camera.

The second phase consisted of the development of the algorithms and the linking of the software and hardware necessary for the correct functioning of the system, from the microcontroller to the reaction wheel. Likewise, small tests were carried out as subsystems were integrated. The manufacturing was carried out with 3D printing and the components used were COTS type, opting to use an ESP32 microcontroller for its connectivity and communications features, and opting for an ESP-CAM for its synergy with the ESP32. On the other hand, a proportional control algorithm was designed for the cubesat control system.

Finally, for the testing phase it was necessary to suspend the cubesat on the axis on which the reaction wheel was arranged. Subsequently, orientation and data reception tests were carried out to verify the correct functioning of the control and communications system.

2.1. Equipment selection

The design of the algorithm began with the selection and incorporation of each of the instruments and their respective interfaces/libraries necessary to function properly.

2.10a. Solar sensor: The solar cells used in the electrical power system will be used .

2.10b. Magnetometer: They are sensors that measure magnetic fields. The ESP32 board has a built-in magnetometer for Hall effect measurement. Although this sensor is not capable of measuring the direction of the magnetic field, it is sufficient to provide its magnitude and orientation with respect to the plate, since the primary orientation of the sensor will be given by the IMU.

Placa	Arq.	Vel. reloj [MHz]	Voltaje [V]	Pines (digitales Análogos PWM)	Pines protocolo	Wireless	Sensores	Lenguajes	Memoria (SRAM Flash EEPROM)	Dimensiones (LxH) [mm]	Masa [g]
Arduino nano	8 bit RISC	16	5	D: 14 A: 8 P: 6	SPI: 1 I2C: 1 UART: 1	No	No	Arduino IDE C/C++	S: 2 kb F: 32 kb E: 1 kb	45x18	7
ESP32	32 bit LX6	240	3.3	D: 36 A: 16 P: 15	SPI: 4 I2C: 4 UART: 2 I2S: 2	WifiHT20 Ble4.2	Touch Temperatura Hall effect	Arduino IDE C/C++ Micro Python	S: 520 kb F: 4 Mb	51x23	6.8
Raspberry Pi Pico	32 bit ARM	133	3.3	D: 26 A: 16 P: 3	SPI: 2 I2C: 2 UART: 2	No	Temperatura	Micro Python C C++	S: 264 kb F: 2 Mb	51x21	5.5

Figura 2: Flight computer comparison.

2.10c. Gyroscope and accelerometer: They are sensors that measure the rate of angular change of the ship. The MPU6050 module or IMU is the most popular for calculating acceleration and angular velocity within the microprocessor market. This is due to its economical value, precision (thanks to its 16-bit A/D converters) and simplicity. It has a lot of technological maturity and a large amount of information on its use, which makes it very reliable. You can see its data in the table 1 [7].

2.10d. Star trackers or cameras: They are optical sensors that provide the direction and rate of change in the direction of the ship's positioning vector. This requires a camera that can obtain images of the celestial field and compare them with the stored data.

2.11. Actuators: The attitude determination and control system actuators allow rotation of the satellite in a direction of interest. As seen in the introduction, there are 3 different types of actuators used to control the orientation of satellites. Reaction wheels have the advantage of having greater technological maturity, simplicity, reliability and greater torque. All this in contrast to magnetocouples that do not produce large spins due to their dependence on the small Earth's magnetic field, reducing precision and generating difficulties in the development of the mission. And, also in contrast, to the propellants, which do not have great technological maturity and are much more complex and unreliable. For all of the above, it was decided to select the reaction wheels as the satellite's control and steering system.

There are many options on the market to design and build a control system based on reaction wheels. Due to its simplicity and low cost, it was decided to follow the design presented by Mangala et al. [3] in which a system of 3 brushless DC motors with their respective ESCs or speed controllers is used, as seen in figure 1. In this case, we worked with a brushed DC motor and a L298N controller because the ESP32 Libraries doesn't permit a good connection and control of the brushless motor. [3].

Brushed motors have a wide range of options that especially depend on their usefulness. Due to their low cost and versatility, the first option is to work with the 6-12 DC commercial motor, which are generic robot and electric motors. This motor is seen in the figure 3 and its characteristics are presented in the table 2 [8].

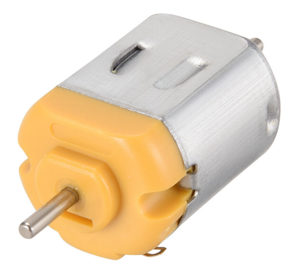


Figura 3: 2212 brushless motor [8]

2.2. *Algorithm Design*

The algorithm was carried out using the Arduino interface due to its great control capabilities and compatibility with the ESP32 board. To connect the MPU6050 sensor, the library from the supplier Adafruit was used. On the other hand, the Arduino sketch data upload tool was used, which allows content to be stored within the SPIFFS memory of the board. Finally, to use the motor through the L298N controller, no additional library is required since it works with digital pins. The libraries and additional information for the rest of the subsystems will be omitted.

Although the code will not be shown in detail, its operation and logical sequence will be explained. Firstly, the board starts the adafuit library by connecting to the MPU6050 sensor in I2C communication and receiving data from it directly. Secondly, the board starts the web page using the html5 files previously stored in SPIFFS memory. The interface was made based on the one presented in [] shown in figure . The design of this page is relatively simple, javascript was used to animate the movement of the cubesat in 3D and the arduino library ESPAsyncWebServer to send the sensor data and receive the target position from the client. The final design is shown in the figure 4.

The algorithm constantly calculates the error as the difference between the angle desired by the user and the sensor angle. Subsequently, it detects the direction of rotation closest

Tabla 1: MPU6050 IMU Sensor

Description	Mass (g)	Dimensions (mm)	Voltage (V)	Protocol	Range gyroscope (°/s)	Range accelerometer (g)	Cost (COP)
MPU 6050	3	2 x 1.6 x 0.1	3-5	I2C	±250 - ±2000	±2 - ±8	10,000

Tabla 2: Motor technical data.

Description	Masa (g)	Force (N)	Power (W)	Voltage (V)	Cost (COP)
brushless 2212	54	8,8	191,5	11,1	38.000

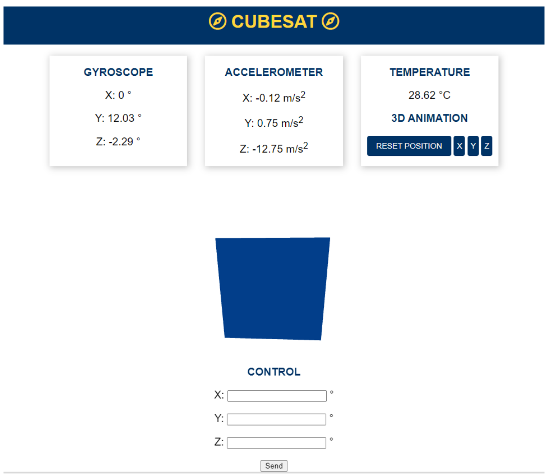


Figura 4: final design of web page.

to the desired angle and assigns a normalized value (depends on controller design) to the angular distance to the desired position so that the engine is activated with this speed and corrects it as it approaches the desired point.

2.3. *Controller design*

For the design of the controller, 3 methodologies were proposed with the objective of comparing their results and precision: Theoretical proportional controller, theoretical PID controller and experimental PID controller starting from the design of a model of the reaction wheel.

2.30a. Electrical and mechanical model of the reaction wheel: Reviewing the figure 5 where the physical model

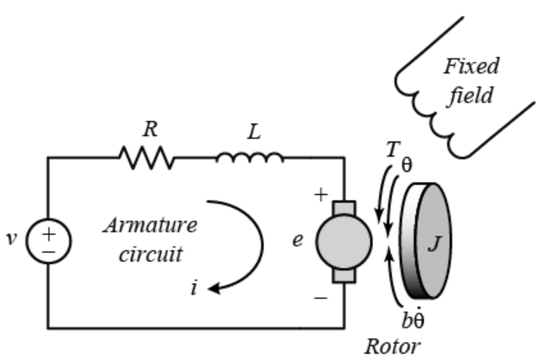


Figura 5: Reaction wheel circuit (dc motor)

Figura 6: Caption

Variable	Description	Magnitude
V	Voltage	6 V
Kb	Amplifier Gain	0.02604
Ra	Resistance	15.2 ohm
La	Inductance	10 H
Ja	Inertia motor	0.4 kg*m2
B	Damping	0.00564 Nms
Km	DC motor constant	0.00415Nm/s

Tabla 3: Model coefficients [10][11]

of the DC motor is presented, it is possible to determine that there are two sections within the model: electrical and mechanical dynamics. Electrical dynamics consists of the current conduction section from the battery to the motor, while mechanical dynamics consists of the transmission of the electrical power received in the motor to the motor shaft.

From the electrical and mechanical dynamics of the reaction wheel we get [9]:

$$L_a \frac{di_a}{dt} = V - i_a R_a - K_b W_m \tag{1}$$

$$J \frac{dW_m}{dt} = K_m i_a - B W_m \tag{2}$$

the variables and its values are presented in table 3

From these equations, we can draw the block diagrams of the reaction wheel model in simulink. this block is shown in

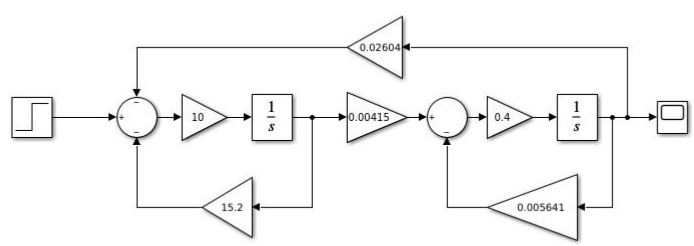


Figura 7: Block diagram of a satellite's reaction wheel

2.30b. Proportional controller: Initially, a proportional controller was designed that corrected and performed feedback control by multiplying the error value by a constant, called proportional control constant. The simplicity of this type of controller causes the system to take longer to stabilize and oscillate quite a bit.

The proportional control constant was desired based on methodology described by Ogatta [12]: Firstly, calculate the closed loop transfer function of the system using a constant of the proportional controller. It is then compared with the general second-order transfer function, and an equation for damping ratio and undamping natural frequency is obtained. The other two necessary equations are obtained by setting a design condition such as settling time and maximum overshoot. The three equations of design are 3, 4 and 5:

$$F = K\frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{3}$$

$$T_s = \frac{4}{\xi\omega_n} \tag{4}$$

$$M_p = e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \tag{5}$$

The proportional controller constant obtained by this method is introduced then in the arduino code.

2.30c. PID controller: Subsequently, a proportional-integral-derivative controller was designed to verify the improvement in the stability and oscillation of the system in the face of disturbances. The block diagram of the PID controller is shown in Figure 8.

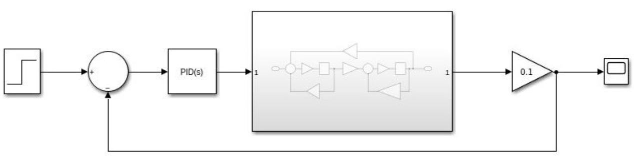


Figura 8: PID controller in simulink

2.30d. Experimental PID controller: By designing the cubesat system and building it with the help of 3D printing, the test prototype in the figure 9 was obtained, with which tests of the control system were carried out simulating a zero gravity environment in a single axis with the use of attached ropes to the system.

Additionally, using the Arduino Serial, the data was obtained that was imported into Matlab and subsequently used in the systemIdentifier and PID tunner tools that allow the simple and intuitive design of a controller for a plant or system.

3. Results

Testing the system using the data from the proportional controller obtained, the graph in the figure 10 was obtained, which will be used as an initial system for the design of the robust PID controller.

Using simulink's PID tuner, the following results were obtained:

Likewise, the response of both the system with and without PID controller was obtained and is shown in figure 11

Figura 9: Testing protoype.

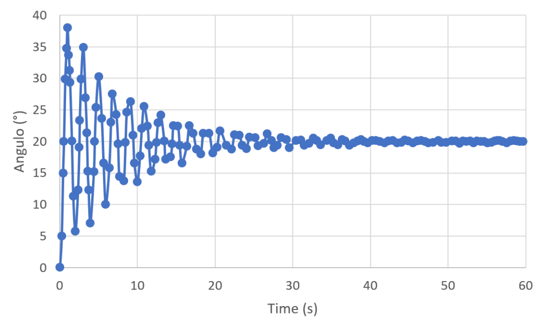


Figura 10: System testing with P controller.

Kp	Ki	Kd
18.761	0.745	1.75

Tabla 4: values obtained from simulink tuner

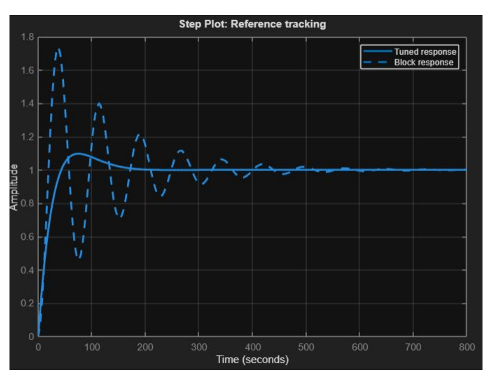


Figura 11: System response with tuned PID compared to system response without PID (block)

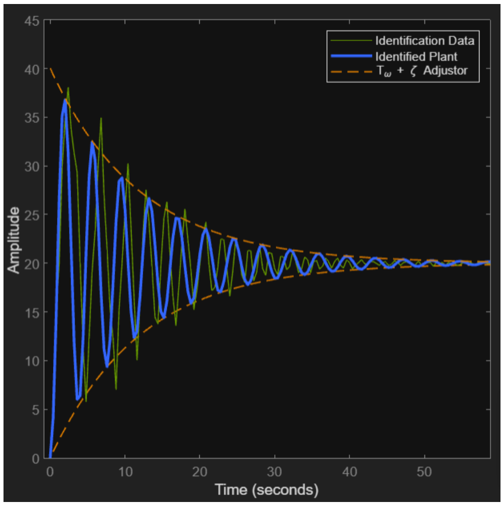


Figura 12: Plant identification results

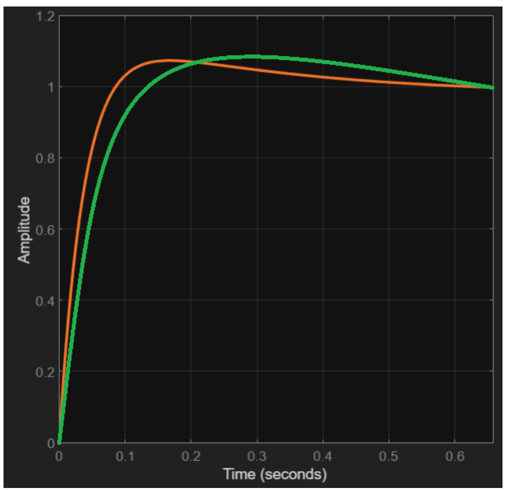


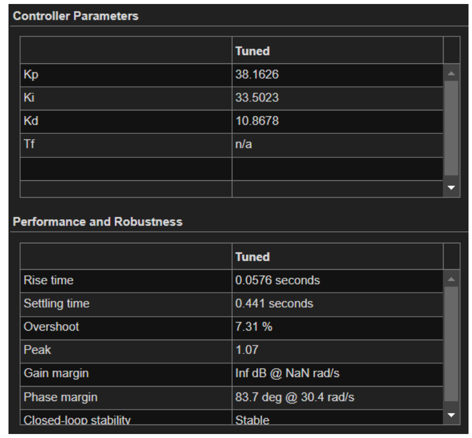
Figura 13: PID controller design comparison. Orange line is the simulation and green line is the testing of the controller.

Finally, using the initial system obtained with the proportional controller, the matlab systemIdentification and PID tuner tool was used to adjust a plant or system to the data and design a PID controller based on this plant.

The plan shown in the figure 12 was obtained from the systemIdentification tool, using the data from the previous system. Subsequently, a PID controller is designed for the plant with PID tunner where, by manually adjusting the controller curve, the graph in the figure 13 is obtained, with the data in the figure 14. Additionally, the curve obtained when testing the controller in the physical system of the cubesat was added.

4. Discussion

The behavior of the system obtained theoretically in the figure 11 and experimentally in the figure 10 suggests that the system behaves in the same way because the shape of the graph is similar, but the stabilization times and peak values



Controller Parameters

	Tuned
Kp	38.1626
Ki	33.5023
Kd	10.8678
Tf	n/a

Performance and Robustness

	Tuned
Rise time	0.0576 seconds
Settling time	0.441 seconds
Overshoot	7.31 %
Peak	1.07
Gain margin	Inf dB @ NaN rad/s
Phase margin	83.7 deg @ 30.4 rad/s
Closed-loop stability	Stable

Figura 14: PID controller information.

vary given, possibly due to the imprecision of the engine dynamic values used.

In the results obtained it can be observed that the response of the controller without pid oscillates and takes about 400 seconds to stabilize, this is believed to be because the values of the coefficients obtained for the model (Table 3) may not correspond to the real values, on the other hand, the response of the PID controller with the simulink tuner tool stabilizes and does not oscillate considerably.

On the other hand, the controller obtained by the experimental method of figure 13 efficiently adjusted the system by reducing the settling time and the overshoot at the input step. Using the values of the controller constants within the Arduino environment and the ESP32 board, it was possible to prove that the system behaves identically to that obtained by the simulation.

5. Conclusions

To conclude, tools such as matlab and simulik are of great help for modeling control systems, these tools are well known, have a large community and are easy to use, ideal for academic projects. On the other hand, it has been shown that PID controllers can improve the response of control systems when they are implemented, as has been shown in this case, since the model without the PID controller has had an inferior performanthe real world.

6. Recomendations

In future work, it is advisable to use higher precision sensors and a prototype architecture that allows reducing the error when trying to simulate the zero gravity environment.

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