ISSN 1870-4069

Fuzzy Control of a Self-Balancing System: An Approach for Satellite Attitude Determination and Control System Testbed

A. de J. Pablo-Sotelo[1,2], María Elena Aguilar-Jáuregui[3], A. Luviano Juárez[1],
Cuauhtemoc Peredo-Macías[3], J. J. Hernández Gómez[2]

[1] Instituto Politécnico Nacional,
Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías
Avanzadas,
Ciudad de México, Mexico

[2] Instituto Politécnico Nacional, Centro de Desarrollo Aeroespacial,
Ciudad de México, Mexico

[3] Instituto Politécnico Nacional, Centro de Investigación en Computación,
Ciudad de México, Mexico

`abraham_pablo_11@hotmail.com`

Abstract. In the development of satellite systems, rigorous validation of constituent subsystems is imperative. Among the various subsystems that compose a satellite, the Attitude Determination and Control System (ADCS) plays a crucial role in maintaining satellite orientation and stability. The validation process for these subsystems traditionally employs test benches capable of simulating space environment conditions. However, simulating such an environment presents numerous challenges, a significant one being the imbalance caused by the discrepancy between the satellite's center of mass and its geometric center, which can substantially affect test conditions and results. This work presents a simplified design of a single-axis balancing system for a 1U CubeSat ADCS testbed. The system utilizes a fuzzy controller designed to operate a sliding mass, which corrects internal system perturbations for the initial configurations of satellite tests.

Keywords: Fuzzy control, satellite control, attitude determination and control system, self-balancing, hardware-in-the-loop test.

1 Introduction

Attitude Determination and Control System (ADCS) is a critical subsystem responsible for managing a satellite's orientation in space. It plays a crucial role in ensuring the success of space missions. The ADCS performs several vital functions, such as orienting solar panels to maximize energy collection, aligning satellite antennas with ground stations to facilitate communication, and directing scientific instruments towards specific celestial bodies or regions of interest. In the context of CubeSats, a class of small satellites, the implementation of ADCS varies. While not all CubeSats incorporate an ADCS, the majority do include this subsystem, with only a few exceptions. The decision to include an ADCS in a CubeSat depends on the specific mission objectives, power constraints, and complexity of the satellite.

1.1 Verification of Attitude Determination and Control Systems of CubeSats

Satellite orientation and stability control systems require rigorous testing before deployment. To address this problem, advanced testing equipment has been created that simulates the conditions in space [13, 15, 17, 19, 24].These platforms, integrate various mechanical, electrical, and control components to recreate the challenges a satellite will face in space. The primary function of these testbeds is to evaluate the effectiveness of a satellite's ADCS. By simulating space conditions, these platforms enable to:

1. Assess the ADCS performance,
2. Detect potential malfunctions,
3. Implement necessary adjustments.

This process is crucial for ensuring the satellite's proper functioning once in orbit. For CubeSats test benches these typically incorporate three key elements [14]:

- An air bearing system for frictionless rotation,
- A mechanism to generate simulated disturbances,
- A Helmholtz cage for magnetic field simulation.

The versatility of these test benches allows for a range of verification procedures. These are generally categorized into two main types of testing:

- Hardware-in-the-Loop (HIL) Test: Evaluates real hardware components in a simulated environment, combining physical and virtual elements to test system performance under realistic conditions [1, 21, 23].
- Software-in-the-Loop (SIL) Test: Assesses control algorithms in a fully virtual environment, allowing for rapid iteration and debugging of software without physical hardware constraints [6, 7, 10].

One of the inherent challenges in developing testbeds for ADCS systems is balancing the testbed itself, as discussed in [4]. The testbed must initially perform a balancing procedure to establish the initial test conditions. While various solutions have been proposed in the literature, the most widely accepted method is manual balancing [9, 12, 20]. However, this approach is inherently susceptible to multiple human-related issues.

1.2 Fuzzy Control

Fuzzy control, based on fuzzy logic introduced by Zadeh in 1965 [27], is a control and decision-making approach that allows working with imprecise and vague information, similar to human reasoning.

This approach is fundamental in situations where strict data precision is not possible or necessary, and a more flexible and adaptable interpretation of information is required. Fuzzy sets employ membership functions that assign a degree of membership (usually between 0 and 1) to each element of the set, allowing for the representation of vague or imprecise concepts [16 , 26].

Unlike conventional control methods, fuzzy control does not require a precise mathematical model of the system, making it particularly useful for nonlinear systems with a high degree of uncertainty [18, 22].

This approach allows for the incorporation of expert knowledge in the form of linguistic rules, facilitating the implementation of control strategies based on human experience. Furthermore, fuzzy control can efficiently manage multiple input and output variables, making it suitable for complex multivariable systems.

In the context of satellite test systems, specifically for ADCS, fuzzy control offers significant advantages, as demonstrated in [3, 5, 8]. The nonlinear nature of the balancing system (as shown in [4]), coupled with the need to handle multiple variables such as inclination angle and angular velocity, makes fuzzy control an attractive option.

The ability to incorporate expert knowledge about system behavior can lead to more robust and adaptable control.

Compared to classical control methods like PID, fuzzy control can offer better performance in nonlinear systems and may be easier to adjust in situations where the exact mathematical model of the system is difficult to obtain or changes over time. It is worth noting that the combination of classical controllers such as PID and fuzzy controllers has been extensively studied, as shown in the literature [2, 11, 25].

2 Fuzzy Controller

The following section presents a conceptual model that closely approximates a real ADCS testbed, addressing the single-axis balancing problems described in Section 1.1. This model serves as a foundation for understanding and analyzing the dynamics of the system in a controlled environment.

2.1 Description of the system

The system used to study mass balancing systems in ADCS testbeds is shown in Figure 1.

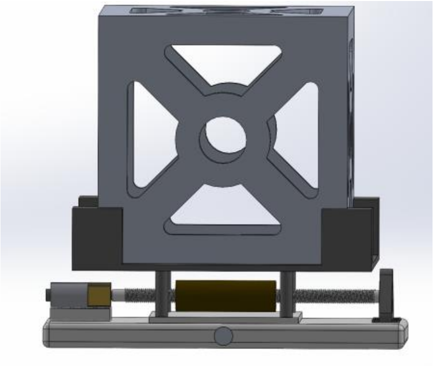

Fig. 1. A frontal view of the system with a 1U CubeSat mounted.

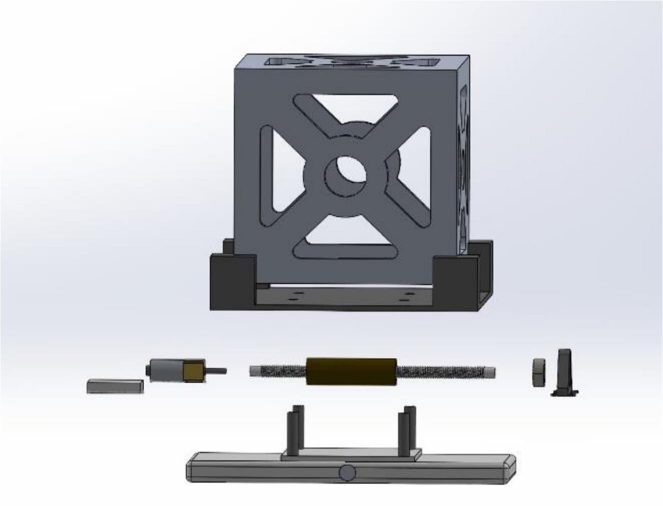

Fig. 2. Exploded view of the system.

It is important to note that while this design deviates from the characteristic configuration of manual balancing systems for verification purposes, it retains similar functional attributes.

Specifically, it incorporates a mass that traverses beneath the satellite, aiding in the compensation of the discrepancy between the center of mass and the geometric center of the CubeSat.

At this stage, it should be observed that low-friction environmental conditions have not been incorporated into the model. Figure 2 presents an exploded view of the system, offering a comprehensive visualization of all constituent components.

Table 1. System Components (see Figure 2)

Component	Function	Technical Specification
Lead Screw	Displaces the mass to correct centre of mass	M5-0.8×100 worm screw
Motor	Actuates the corrective mass	Pololu Micro Metal Gearmotor MP 6V with 12 CPR Encoder 298:1
Sliding Mass	31.46g corrective mass	Galvanised steel
Encoder	Measures system inclination via rotational displacement at the base pivot	5000-pulse incremental magnetic encoder

Table 2. Signals of the fuzzy system.

Name	Type	Description
Inclination Angle (θ)	Input	Represents the beam's inclination relative to an inertial frame located at the system's pivot, measured by an incremental encoder
Angular Velocity $\dot{\theta}$	Input	Rate of change of the inclination angle with respect to time *t*
Mass Displacement (μ_1)	Output	Required displacement to generate a balancing torque for the system

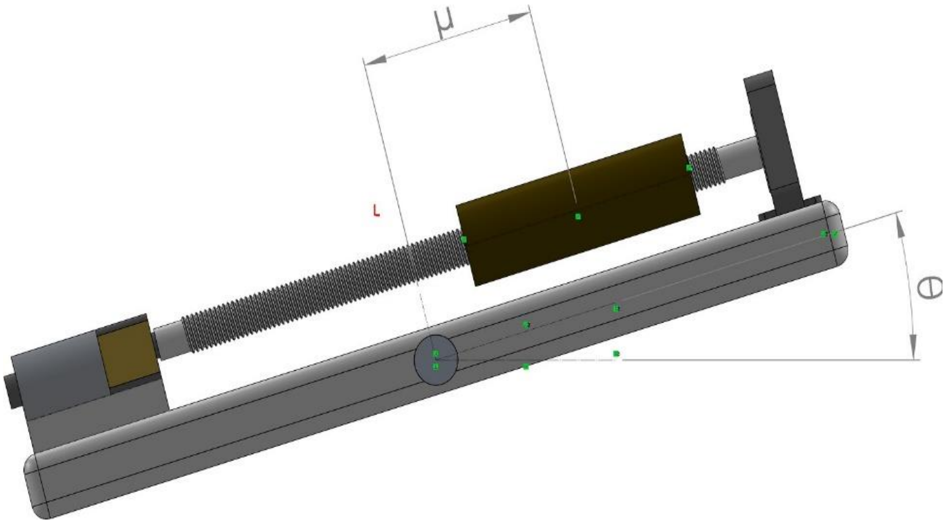

Fig. 3. System without CubeSat.

Table 3. Sets for the error variable.

Inclination Angle [degrees]	**Set**
-90 to -0.5	Very Low Error (*V LE*)
-1 to 0	Low Error (*LE*)
-0.5 to 0.5	Zero Error (*ZE*)
0 to 1	High Error (*HE*)
0.5 to 90	Very High Error (*V HE*)

Table 4. Sets for the angular velocity variable.

Angular velocity [degrees/sec]	**Set**
-2 to 0	Low Velocity (*LV*)
-0.5 to 0.5	Zero Velocity (*ZV*)
0 to 2	High Velocity (*HV*)

Table 5. Sets for the mass displacement variable.

Displacement [meters]	**Set**
-0.05 to -0.01	Very Low Position (VLP)
-0.02 to 0	Low Position (LP)
-0.01 to 0.01	Zero Position (ZP)
0 to 0.02	High Position (HP)
0.01 to 0.05	Very High Position (VHP)

Table 6. Control Rule Matrix.

		Angular Velocity		
		HV	ZV	LV
Error	VLE	HP	VHP	VHP
	LE	HP	HP	VHP
	ZE	LP	ZP	HP
	HE	LP	LP	VLP
	VHE	LP	VLP	VLP

Furthermore, Table 1 provides a detailed description of the most salient components, highlighting their roles and significance within the overall system architecture. Given the encoder specifications described in Table 1, the system achieves an angular resolution of 0.072°.

Additionally, the maximum displacement velocity of the mass, determined by the worm screw and motor characteristics, is approximately 0.001467 m/s. For the purposes of this study, Figure 3 shows the essential elements crucial to the design of the fuzzy controller.

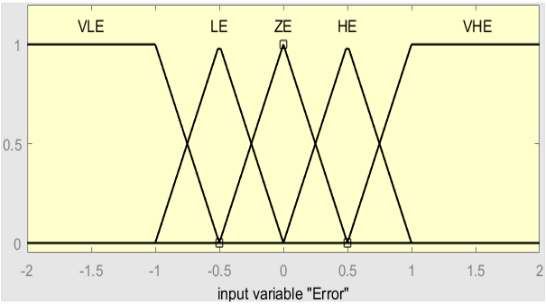

Fig. 4. Membership function of the error variable.

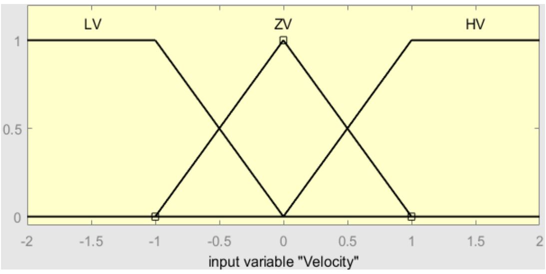

Fig. 5. Membership function of the angular velocity variable.

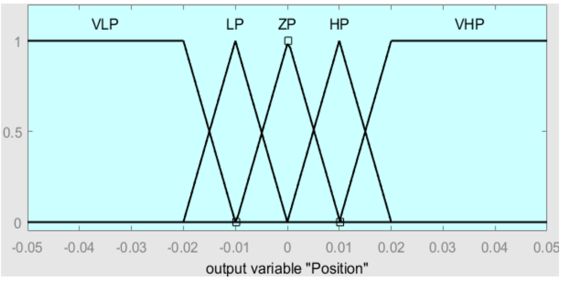

Fig. 6. Membership function of the mass displacement variable.

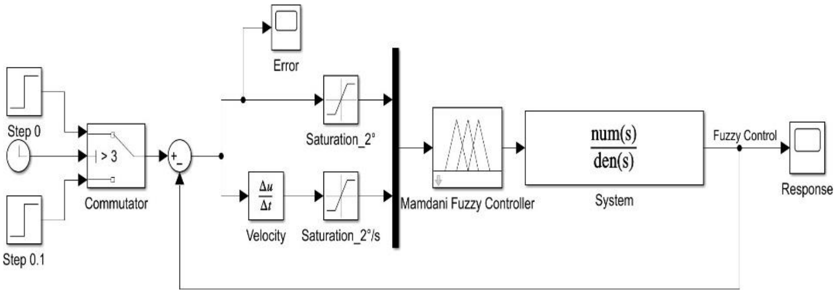

Fig. 7. System model and fuzzy control.

2.2 Fuzzy Control Design

The following section details the design of the fuzzy control system for the setup showed in Figure 1.

2.3 Linguistic Variables of the System

Table 2 presents the linguistic variables of the system, along with a concise description of their role within the fuzzy controller.

2.4 Functional Description of the System

The following presents a brief and simplified functional description (See Table 6 to observe the control behavior) of the system:

If the system's inclination is very high and this inclination is rapid, the mass displacement is high. If the system's inclination is very high and this inclination is slow, the mass displacement is low. If the system's inclination is very high and the velocity is zero, the mass displacement is low. If the system's inclination is very low and the velocity is very high, the displacement is high.

2.5 Definition of the Sets

The error variable is derived from the incremental encoder located at the system's pivot. For this linguistic variable, the universe of discourse is defined from -90° to 90°, and the sets are represented in Table 3.

The selection of sets for the angular velocity variable follows a similar approach to the previous set. However, it is described by the angular velocity in degrees per second, as shown in Table 4.

Finally, Table 5 describes the set for the mass displacement variable, which is defined by the dimensions of the lead screw.

2.6 Control Rule Sets

The control rules are entirely dependent on the experience of the control system designer. Due to the number of variables, a two-dimensional matrix is generated, derived from the functional description of the system. Given the behavior of the system's linguistic variables, it is possible to describe the fuzzy control through the matrix in Table 6.

Based on the control matrix, the following structure is used for the propositions: ***IF*** *premise 1* ***AND*** *premise 2* ***THEN*** *consequent.*

Here the consequent is the output variable (mass displacement variable). Below are all the compound propositions of the system:

If $E = VLE$ **and** $V = HV$ **then** $P = HP$
If $E = VLE$ **and** $V = ZV$ **then** $P = VHP$
If $E = VLE$ **and** $V = LV$ **then** $P = VHP$

If $E = LE$ **and** $V = HV$ **then** $P = HP$
If $E = LE$ **and** $V = ZV$ **then** $P = HP$
If $E = LE$ **and** $V = LV$ **then** $P = VHP$
If $E = ZE$ **and** $V = HV$ **then** $P = LP$
If $E = ZE$ **and** $V = ZV$ **then** $P = ZP$
If $E = ZE$ **and** $V = LV$ **then** $P = HP$
If $E = HE$ **and** $V = HV$ **then** $P = LP$
If $E = HE$ **and** $V = ZV$ **then** $P = LP$
If $E = HE$ **and** $V = LV$ **then** $P = VLP$
If $E = VHE$ **and** $V = HV$ **then** $P = LP$
If $E = VHE$ **and** $V = ZV$ **then** $P = VLP$
If $E = VHE$ **and** $V = LV$ **then** $P = VLP$

2.7 Membership Functions

Finally, the following membership functions are established for each set of linguistic variables in the system. Figure 4 shows the membership function corresponding to the error variable.

This distribution for the membership functions was constructed based on the operating ranges shown in the literature [9, 12, 20]. Note that the system's efficiency may vary depending on the type of function; this will be addressed in depth in the conclusions of this work. For the membership function of the angular velocity, only three velocities will be considered. Efficient results were shown in the simulations presented in Section 2.3 within the context of this work. Lastly, due to the dimensions of the mobile bar and the moment-generating mass, the following membership function is established (see Figure 6).

2.8 Simulations

The fuzzy controller is validated through numerical simulation using Matlab ® Simulink tool, version R2023b. The Simulink model of the fuzzy controller is shown in Figure 7.

The system response under these conditions is shown in the graph in Figure 8. Finally, the corresponding modification is made in the Simulink model to obtain the system's response to an initial condition of 2° and its response to a reference of 0°, which is showed in Figure 9.

3 Results and Conclusions

The fuzzy controller, as shown in Figure 8, was subjected to tracking two references (the same ones illustrated in the Simulink model in Figure 7). To reach the position of 0.1° inclination, the system achieved its settling time in approximately 1 second, and exhibited an overshoot of 0.024° for the 0.1° reference.

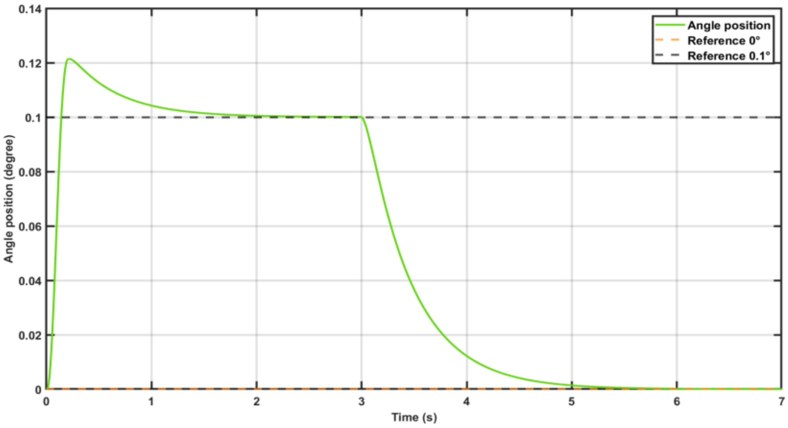

Fig. 8. Response of the fuzzy controller to references of 0.1° and 0°.

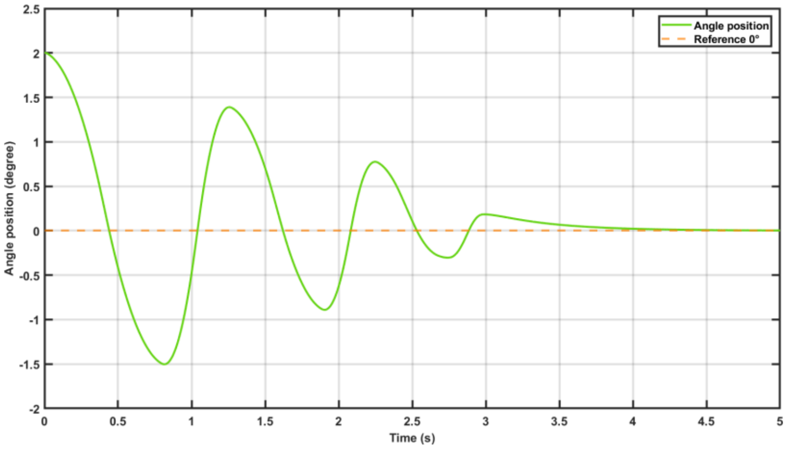

Fig. 9. Response of the fuzzy controller to reference of 0°.

On the other hand, to reach the 0° position starting from a 0.1° deviation, the settling time is achieved in approximately 1.2 seconds with an almost imperceptible overshoot of 0.001°. Finally, the case closest to the real application was presented, which starts from a system with a 2° deviation (see Figure 9). In this case, a settling time of 3.4 seconds was observed, and an overshoot above the 0° reference level of approximately 1.5°, which, although significantly large, does not affect the model's objectives.

The fuzzy control system was successfully designed for a single axis to balance an ADCS test system. This design effectively addresses the issues arising from human manipulation and calibration inherent in all manual systems presented in the literature. While not optimal, the performance metrics of the controller are sufficient to meet the requirements for balancing systems in ADCS testbed, considering the scope of this work. The system's linguistic variables, their sets, and membership functions were defined, along with the control rules. This approach allows for the incorporation of expert knowledge and the handling of system nonlinearities. Future work could explore the optimization of the fuzzy controller using techniques such as genetic algorithms to further enhance its performance. Additionally, we could consider systems with a greater number of membership functions or different geometries (e.g., sigmoidal) to potentially enhance system performance. However, it is important to avoid too many functions near 0° to prevent exceeding the capabilities of the selected encoder. These improvements might help reduce the overshoot and settling time, potentially leading to better system performance.

Acknowledgments. The authors acknowledge partial economical support by projects 20242752, 20240894, 20241163, 20241077 and 20240811, as well as EDI and PIFI grants, provided by Secretaría de Investigación y Posgrado, Instituto Politécnico Nacional.

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