ALGERIAN JOURNAL OF ENGINEERING AND TECHNOLOGY

Algerian Journal of Engineering and Technology
ISSN: 2716-9227 (Print)
EISSN: 2716-9278 (Online)
DOI: https://doi.org/10.57056/ajet.v9i1.164
Roubache et al / vol. 09, n°1 - 2024

Original Article Open Access

Adaptive Nano Satellite Attitude Control Design under Multiplicative Actuator Uncertainties

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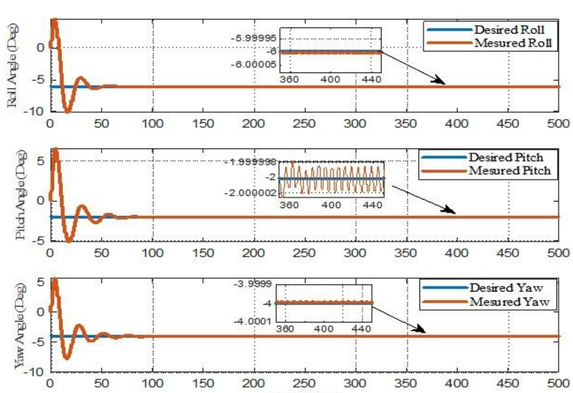
Article history: Received 27 November 2023, Revised 09 March 2024, Accepted 12 March 2024

ABSTRACT

The utilization of nanosatellites in space missions has sparked significant interest owing to their compact size and relatively economical development, launch, and operational expenses in comparison to larger satellites. This cost-effectiveness facilitates more frequent launches and the capability to replace or upgrade satellites with greater frequency. The stability of nanosatellites is paramount for their successful operation in space, necessitating designers and engineers to implement various measures to ensure the satellite maintains its orientation and position throughout its mission. In this paper, an adaptive control methodology relies on backstepping control theory is suggested to address the multiplicative faults in the actuators. Specifically, the control system's efficacy is demonstrated through numerical simulations for 3-axis stabilization. The outcomes reveal that the proposed control approach adeptly sustains the stability of the nanosatellites in the event of actuator failure, outperforming classical backstepping control.

Keywords: backstepping control; attitude control; nanosatellite; multiplicative fault observer; adaptive algorithm.

Graphical abstract



Time responses of Desired and estimated attitude - Adaptive backstepping

Recommended Citation
Roubache R , Benmansour JE, Adnane A. Adaptive Nano Satellite Attitude Control Design under Multiplicative Actuator Uncertainties. *Alger. J. Eng. Technol. 2024, 9(1): 104-113.* https://doi.org/10.57056/ajet.v9i1.164

1. Introduction

In numerous satellite missions presently operational, spanning applications such as scientific research, Earth observation, and navigation, attitude control plays a pivotal role. It involves actively overseeing and fine-tuning the satellite's orientation to fulfill specific goals. These objectives encompass precise alignment of the satellite's payload with Earth-based targets, ensuring stability to prevent undesirable tumbling motions, optimizing solar panel power generation, and facilitating efficient communication with ground stations. Within the domain of nanosatellites, utilized for diverse research and military missions, specific requirements and constraints guide distinct considerations in managing attitude [1], [2], [3].

To alter the satellite's orientation, a combination of active and passive actuators can be employed. Passive actuators typically involve rigid ferro-magnetic masses that leverage the Earth's gravitational field. While this method offers only an approximate orientation of the satellite [4], [5], it lacks

precision. Conversely, various active actuators, such as magnetorquers, reaction wheels, thrusters, and gyroscopic wheels, offer more accurate control over the satellite's orientation.

Actuator-based attitude maneuvering is crucial for satellites to attain the desired orientation, necessitating robust stabilization and precise pointing accuracy. However, the occurrence of faults or failures in the actuator can significantly degrade performance and even lead to attitude instability.

To this end, it is imperative to incorporate fault tolerance into the design of attitude tracking control to ensure the satellite's stability with utmost reliability, as highlighted in existing literature [6], [7], [8]. To achieve this goal, a multitude of control strategies has been recently employed to address the challenges posed by actuator faults in the context of satellite systems [9], [10], [11]. The application of adaptive control has been suggested as an effective approach to tackle the complexities and uncertainties inherent in system dynamics.

Backstepping is a regression design technique that finds an extensive application in the design of satellite attitude control, requiring a well-suited design for external disturbances. Various control strategies have been integrated into backstepping control to enhance attitude control performance, including: adaptive sliding mode control [12], magnetic attitude control [13], attitude containment control [14], Disturbance-observer [15], neural network [16]. These proposed approaches play a pivotal role in ensuring an effective spacecraft attitude tracking under diverse uncertainties.

- This study introduces an adaptive backstepping attitude controller applied to a nanosatellite, aiming to mitigate issues arising from multiplicative faults in the actuator that could potentially impede control performance. The proposed approach incorporates a disturbance observer with an adaptive algorithm to estimate uncertainties. Implementation of this strategy enhances tracking control and improves pointing accuracy.
- The effectiveness of the method in achieving attitude stabilization control for a nanosatellite with uncertain actuator faults is demonstrated through Lyapunov analysis, validating the stability of the closed-loop system under disturbances. Simulation results further support the efficacy of this approach.

2. Mathematical model

The main equation of the satellite attitude dynamics relates the angular momentum with the external torque. This equation, referred to as Euler's equation of motion, is expressed as:

$$I\dot{\omega} = -\omega^{\times}(I\omega + h) + d - u \tag{1}$$

where I, ω, h and d are respectively the moment of inertia of spacecraft the angular velocity vector, the angular momentum of the wheels, and external disturbance torque vector, and u control torque.

The kinematic quaternion of modified Rodrigues parameters is expressed as [17], [18]

$$\dot{s} = G(s)\omega_0 \tag{2}$$

Where

$s=[s_1,s_2,s_3]^T$ is the attitude vector in terms of Rodrigues parameters, $\omega_0=[\omega_{0x},\omega_{0y},\omega_{0z}]^T$ body angular velocity vector referenced to orbital coordinates,

Where

$$\omega=\omega_0+R_r^b(s)w_0$$

And $R_r^b(s)=\frac{1}{1+s^Ts}\begin{bmatrix}1+s_1^2-s_2^2-s_3^2 & 2s_1s_2+2s_3 & 2s_1s_3-2s_2\\ 2s_1s_2-2s_3 & 1-s_1^2+s_2^2-s_3^2 & 2s_2s_3+2s_1\\ 2s_1s_3+2s_2 & 2s_2s_3-2s_1 & 1+s_1^2-s_2^2+s_3^2\end{bmatrix}$

and G is kinematic matrix, it is defined as follow:

$$G(s)=\frac{1}{2}(I_{3\times3}-\frac{1+s^Ts}{2}I_{3\times3}-[s^\times]+ss^T) \tag{3}$$

Where $s^\times$ is an operator formulated as follow [19]

$$s^\times=\begin{bmatrix}0 & -s_3 & s_2\\ s_3 & 0 & -s_1\\ -s_2 & s_1 & 0\end{bmatrix} \tag{4}$$

Finally, by combining the equations of dynamics (1) and kinematic (2) the global system of equations that governs the motion if the satellite around its center of mass is expressed in the following representation:

$$\begin{bmatrix}\dot{s}\\ \dot{\omega}\end{bmatrix}=\begin{bmatrix}G(s)\omega_0\\ I^{-1}\left(-\omega^\times(I\omega+h)+d-\dot{h}\right)\end{bmatrix} \tag{5}$$

3. Backstepping control design

In this part, a backstepping control law is presented. This approach is derived from [20].

The backstepping algorithm is depicted in two basic steps as shown below:

- **Step 1**:

The first and the second variable of the backstepping can be designed as;

$$z_1=x_1=s-s_{ref} \tag{6}$$

$$z_2=x_2-\alpha_1 \tag{7}$$

Where

$x_2=\omega$; and α_1 is a virtual control law.

$$\dot{z}_1=g_1x_2+g_1\alpha_1+f_1 \tag{8}$$

Hence

$$\dot{z}_1=G(s)\omega+G(s)\alpha_1+G(s)R_r^b(s)w_0 \tag{9}$$

In order to prove the stability, we define the first Lyapunov candidate function as:

$$V_1=\frac{1}{2}z_1^Tz_1 \tag{10}$$

Computing the derivative of V_1 gives:

$$\begin{aligned}\dot{V}_1 &= z_1^T \dot{z}_1 \\ &= z_1^T G(s) z_2 + z_1^T (G(s)\alpha_1 + G(s) R_r^b(s) w_0)\end{aligned} \tag{11}$$

To make $\dot{V}_1$ negative α_1 is assumed to be:

$$\alpha_1 = G^{-1}\left(-c_1 z_1 - f_1\right) \tag{12}$$

Where $c_1 > 0 \in R^{3\times 3}$. And

$$f_1 = G R_r^b(s) w_0 \tag{13}$$

substituting (12) in (11) gives

$$\dot{V}_1 = -z_1^T c_1 z_1 + z_1^T G(s) z_2 \tag{14}$$

The term $z_1^T G(s) z_2$ will be discarded in the subsequent step.

- **Step 2**:

The Second Lyapunov candidate function is chosen as follow

$$V_2 = V_1 + \frac{1}{2} z_2^T z_2 \tag{15}$$

Then the derivative of (13) can be written as:

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 + z_2^T \dot{z}_2 \\ &= -z_1^T c_1 z_1 + z_1^T G(s) z_2 + z_2^T \dot{z}_2\end{aligned} \tag{16}$$

According to (7)

$$\dot{z}_2 = \dot{\omega} - \dot{\alpha}_1 \tag{17}$$

Then, substituting (17) and (1) in (16) gives:

$$\begin{aligned}\dot{V}_2 = &-z_1^T c_1 z_1 + z_1^T G(s) z_2 + z_2(-I^{-1}(\omega^\times) I\omega - I^{-1}u \\ &- I^{-1}(\omega^\times) h + I^{-1} d - \dot{\alpha}_1)\end{aligned} \tag{18}$$

To make $\dot{V}_2$ negative, the control law u is assumed to be:

$$u = I(-c_2 z_2 - G z_1 - f_2 + \dot{a}_1) \tag{19}$$

Where

$$f_2 = I^{-1}(d - \omega^\times (I\omega + h)) \tag{20}$$

Hence

$$\dot{V}_2 = -z_1^T c_1 z_1 - z_2^T c_2 z_2 \tag{21}$$

4. Adaptive Backstepping Control design under Actuator Fault

This approach id adopted to design a controller that is able to composite the actuator fault. The concept of this controller is designed as follow.

Considering the presence of actuator faults, the model dynamic equation is consequently rewritten as follow:

$$I\dot{\omega} = -\omega^\times (I\omega + h) + d + (f_m u) \tag{22}$$

Where,

f_m is the additive fault.

The estimated fault errors can be defined as:

$$\tilde{f}_m = \hat{f}_m - f_m \tag{23}$$

Where,

$\hat{f}_m$ is the estimated additive fault.

With the same strategies of section III, we define the first and the second variable of backstepping. Furthermore, since the first subsystem of the mathematical model is defect independent, the first state design of the adaptive backstepping approach is identical as the traditional backstepping and the derivative of the first Lyapunov function remains unchanged.

However, the second Lyapunov function is chosen as:

$$V_2 = V_1 + \frac{1}{2} z_2^T z_2 + \frac{1}{2} \tilde{f}_m{}^T \Gamma^{-1} \tilde{f}_m \tag{24}$$

Where

Γ is a positive design parameter.

Then, the time derivative of (24) can be written as:

$$\dot{V}_2 = \dot{V}_1 + z_2^T \dot{z}_2 + \tilde{f}_m{}^T \Gamma^{-1} \dot{\hat{f}}_m \tag{25}$$

$$\begin{aligned} \dot{V}_2 = & -z_1^T c_1 z_1 + z_1^T G(s) z_2 + z_2(-I^{-1}(\omega^{\times}) I \omega + I^{-1} f_m u \\ & - I^{-1}(\omega^{\times}) h + I^{-1} d - \dot{\alpha}_1) + \tilde{f}_m{}^T \Gamma^{-1} \dot{\hat{f}}_m \end{aligned} \tag{26}$$

Then

$$\begin{aligned} \dot{V}_2 = & -z_1^T c_1 z_1 + z_1^T G(s) z_2 + z_2^T(-I^{-1}(\omega^{\times}) I \omega + I^{-1} \hat{f}_m u \\ & - I^{-1}(\omega^{\times}) h + I^{-1} d - \dot{\alpha}_1) + \tilde{f}_m{}^T \left[-z_2^T I^{-1} u + \Gamma^{-1} \dot{\hat{f}}_m \right] \end{aligned} \tag{27}$$

In order to have a negative derivative, the control law u can be chosen as follow:

$$u = \hat{f}_m^{-1} I(-c_2 z_2 - G z_1 - f_2 + \dot{a}_1) \tag{28}$$

The estimated defect update law is given as follow:

$$\dot{\hat{f}}_m = \Gamma z_2^T I^{-1} u \tag{29}$$

Therefore, the adaptive control law based on backstepping approach is a stable tracking control law on the condition that V > 0 and $\dot{V}$ <0 under the observation of multiplicative actuator faults, afterwards the stability has been demonstrated.

5. Numerical simulations

A numerical simulation was performed using MATLAB and Simulink, to investigate the effectiveness of the selected controller. The following parameters were used to evaluate the results. The inertia matrix is $I = \begin{bmatrix} 1.2 & 0 & 0 \\ 0 & 1.2 & 0 \\ 0 & 0 & 1.2 \end{bmatrix} (kg.m2)$,

The controller gains have been chosen as, $c_1 = 0.5$and $c_2 = 0.1$, and the desired attitude is [-6, -4, -2] deg.

We introduce at the time t=300 sec an additive fault $f_m = 2\ N.m$.

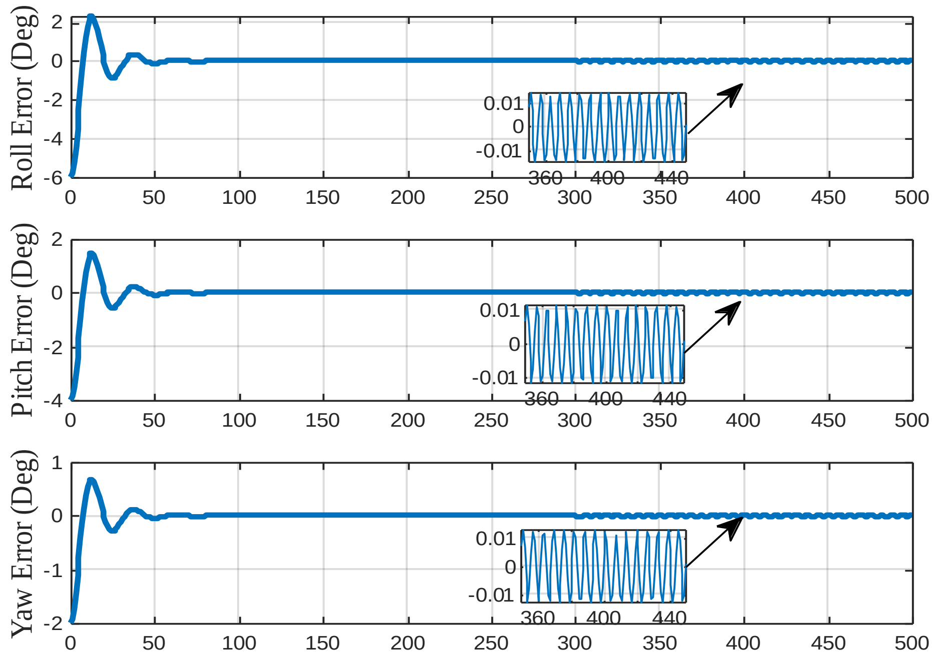


Fig 1. Time responses of Attitude Error-No adaptive backstepping

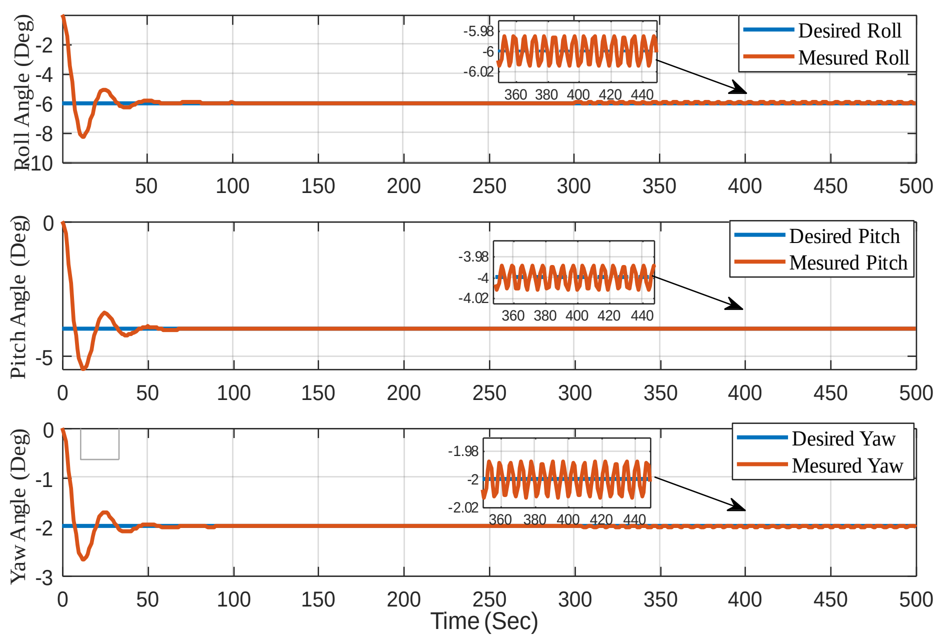


Fig 2. Time responses of Desired and estimated attitude -No adaptive backstepping

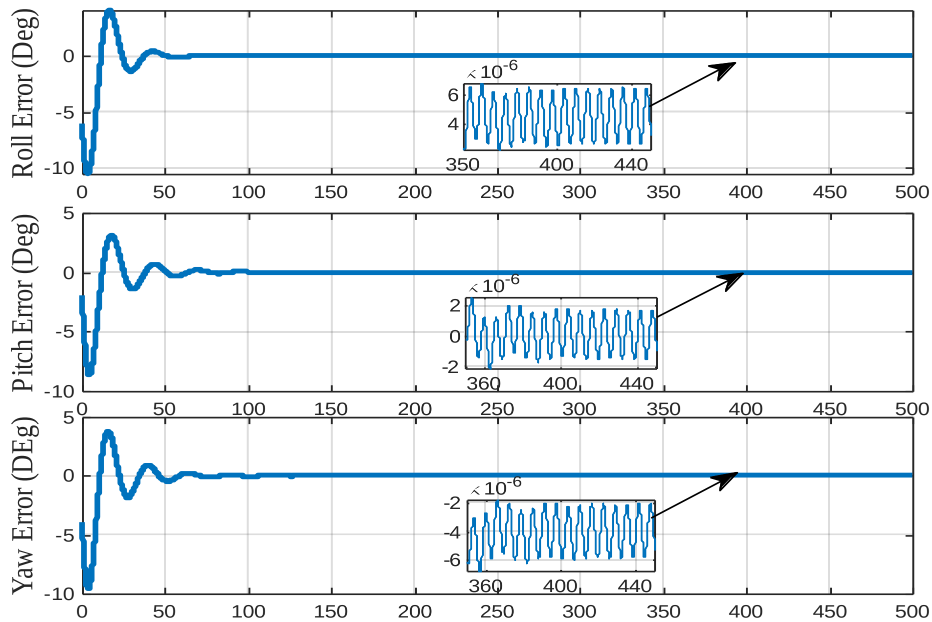


Fig 3. Time responses of Attitude Error-Adaptive backstepping

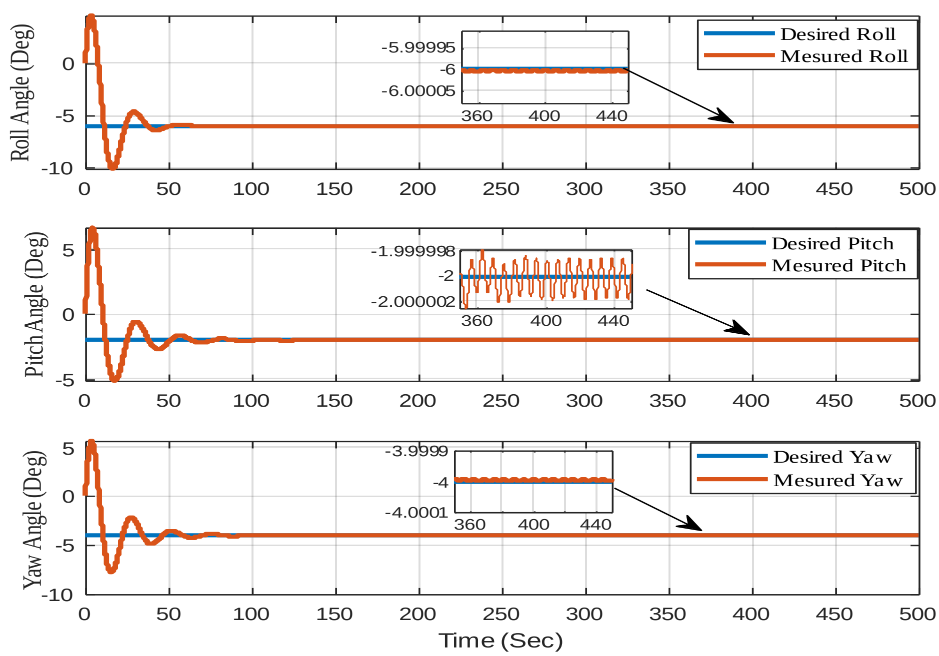


Fig 4. Time responses of Desired and estimated attitude - Adaptive backstepping

In figures 1.2, the representation of attitude and Euler angle errors resulting from non-adaptive backstepping control reveals a substantial impact when subjected to a multiplicative actuator failure at t=300 seconds. It becomes clear that the consequences of this failure are significant, leading to attitude mismatch and, in particular, substantial errors in the Euler angles. This observation underlines the impact of the fault on system dynamics.

The results presented in Figures 3.4 offer a contrasting perspective. These figures show the attitude and Euler angle errors calculated using adaptive backstepping control designed to tolerate actuator failures. Notably, even in the presence of a failure at t=300 seconds, these figures clearly demonstrate that the adaptive control mechanism successfully tracks the desired attitude. This resistance to actuator failure means a significant improvement in system stability, underlining the effectiveness of the adaptive backstepping control approach in maintaining the desired performance despite challenging conditions.

The subsequent analysis provides a more in-depth examination of error results spanning a duration of 350-450 seconds. In this evaluation, the additive fault was considered utilizing the root mean square (RMS) method.Haut du formulaire

Table 1. RMS errors of the attitude

	Root Mean Square Error	
	Backstepping	**Backstepping Adaptive**
Roll (deg)	0.104e-1	0.472e-5
Pitch (deg)	0.081e-1	0.118e-5
Yaw (deg)	0.090e-1	0.424e-5
	Magnitude of error	**Magnitude of error**
Attitude (deg)	0.160e-1	0.646e-5

6. Stochastic Simulations

The static simulation involves approximately 5000 runs, with the primary aim of examining the accuracy and performance of the employed method during attitude control of a rigid nanosatellite. In each Monte Carlo iteration, control errors for angle rates along the three axes are randomly selected within the range of [-0.5, 0.5] with a precision of 0.05°/s. The overall magnitude error is consistently maintained below 0.012 degrees. Across all simulations, the Monte Carlo tests demonstrate the robustness of the adaptive controller against actuator uncertainties, highlighting its effectiveness.

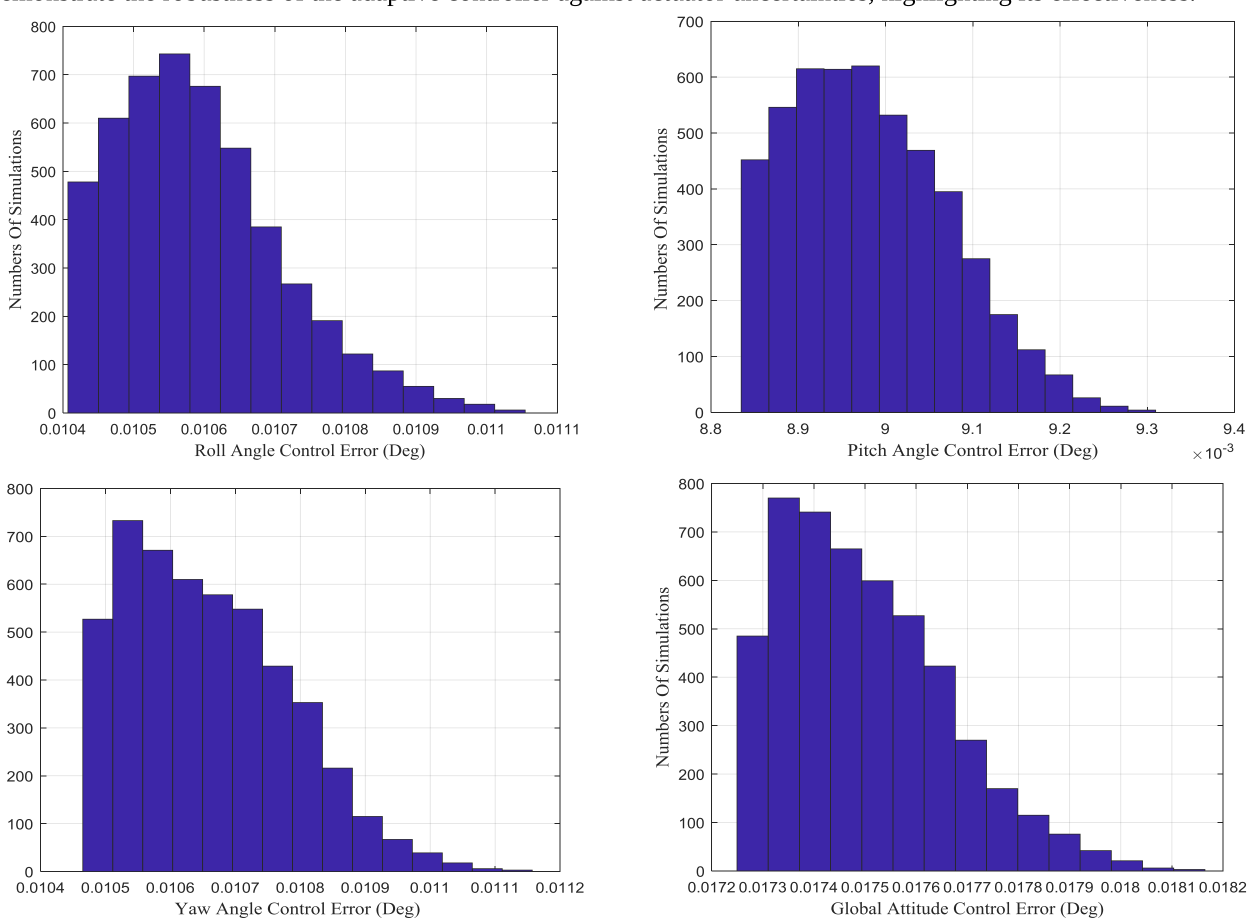


Fig 4. Monte-Carlo simulations test.

7. Conclusion

This paper presents an exhaustive formulation for nanosatellite attitude stabilization suffering from actuator faults. The proposed control methodology relies on an adaptive backstepping controller, with the explicit objective of alleviating the adverse effects of actuator failures on system performance. A Fault estimation observer is incorporated in the proposed adaptive controller to counteract multiplicative actuator faults. A rigorous proof of stability of the closed-loop system is validated through Lyapunov's analysis.in addition, a number of Monte Carlo simulation tests were conducted to assess the performance of the developed adaptive backstepping controller. Finally, the simulation results validate the theoretical claims, demonstrating the effectiveness of the proposed control law across diverse situations, leading to high-precision and consistent attitude control.

Conflict of Interest

The authors declare that they have no conflict of interest.

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