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ATTITUDE CONTROL OF THE NANOSATELLITE USING A HYBRID FUZZY ALGORITHM BY MEANS OF THE REACTION WHEELS

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Abstract. Numerous application fields of automation the industrial processes have demonstrated favorable outcomes with modern control algorithms that rely on artificial intelligence. Therefore, some researchers have endeavored to implement these algorithms in the attitude control of satellites by evaluating their performance in simulated scenarios. However, due to the associated cost and risks, there is a scarcity of experimental data available for testing new attitude control algorithms on a real satellite. To address this issue, simulation of satellite positioning based on the dynamic model of the satellite with reaction wheels was carried out to perform a comparative analysis of a hybrid proportional integral and derivative (PID) fuzzy control algorithm and a classical PID control algorithm, regarding the analysis of the obtained performances. The obtained results indicate that using a Hybrid Fuzzy PID control algorithm produces better performances, than the PID control algorithm.

Keywords: *PID controller, fuzzy logic, attitude control, satellites, Hybrid Fuzzy PID controller.*

Rezumat. Numeroase domenii de automatizare a proceselor industriale au demonstrat rezultate favorabile în utilizare a algoritmilor moderni de control, care se bazează pe inteligența artificială. Prin urmare, unii cercetători au implementat acești algoritmi în controlul atitudinii sateliților prin evaluarea performanței acestora în scenarii simulate. Cu toate acestea, din cauza costurilor și riscurilor asociate, există un deficit de date experimentale disponibile pentru testarea noilor algoritmi de control al atitudinii pe un satelit real. Pentru a rezolva această problemă, a fost efectuată simularea poziționării satelitului în baza modelului dinamic al satelitului cu roți de reacție pentru a efectua o analiză comparativă a unui algoritm de reglare fuzzy proporțional integral și derivativ (PID) hibrid și a unui algoritm de reglare clasic PID, în ceea ce privește analiza de performanțe obținute. Rezultatele simulării au demonstrat că utilizarea algoritmului de reglare fuzzy PID hibrid asigură performanțe mai ridicate în comparație cu algoritmul de reglare clasic PID.

Cuvinte-cheie: *regulator PID, logica fuzzy, controlul atitudinii, satelit, fuzzy PID hibrid regulator.*

1. Introduction

Classical Proportional Integral and Derivative (PID) control algorithm is one of the most common control algorithms used in satellite positioning systems [1]. It can be used to control the movement of the satellite in real time, adjusting its desired orientation in the orbit as needed. In general, classical PID control algorithm is based on three components:

proportional, integral, and derivative. PID control algorithm can be effective for satellite positioning, especially for slow moving satellites. However, there are also situations where a more complex and advanced approach may be required, such as, the use of adaptive controller or other more sophisticated control methods are necessary. The concept of fuzzy controller for orbit and attitude control is a new approach that allows meeting different control requirements with mission specific redesign effort of the satellite.

The concept relies on membership functions and logic rules to analyze the observed state and take appropriate control actions without the need for complex dynamic models. One of the key features of the fuzzy controller is its ability to control the satellite at all stages of the mission without support from ground stations [2]. Classical and state-space satellite attitude control techniques use a linear approach, which is only valid for nominal inertia tensors and small perturbations. Other more complex control techniques, such as adaptive controller or nonlinear controller, better fit the idea of robust control of a system, where the system parameters are not well known, however, these techniques are quite complicated and expensive.

The hybrid fuzzy PID attitude controller provides robust and non-linear control with the ability to be easily adapted to different satellite configurations and missions [3]. Hybrid fuzzy control algorithm represents a more advanced approach to PID control algorithm, which uses fuzzy logic to improve the performance of the control system and reduce errors, and allows a fine adjustment of control parameters according to the specific conditions and requirements. This approach combines the advantages of PID controller, such as the ability to react quickly to the changes in position, with fuzzy logic, which can take into account more factors and provide a more precise and robust control approach.

All critical maneuvers low orbit missions require a high level of autonomy due to reduced visibility from the control station. This means that all onboard operations will be performed on a scheduled basis. To maintain autonomy, an attitude controller must perform all maneuvers without any ground support based only on the initial and final states. The purpose of this paper is to show the characteristics and functional performance of the hybrid fuzzy PID controller in a satellite mission.

2. Structure of satellite

The model of satellite studied in this paper is the CubeSat type. For the correct execution of the missions, the need arises for the correct orientation of the satellites to orient the antennas, to orient a camera, to give a rotational movement to the satellite to avoid overheating of a surface etc. The system that controls the attitude of the satellite is called the Attitude Determination and Control System (ADCS).

The characteristics of the studied satellite are presented in Table 1.

Table 1

Satellite structure characteristics

Description	Value	Unit
Mass	1.00	kg
Moments of inertia I_{xx}, I_{yy}, I_{zz}	0.00235; 0.00235; 0.00166	kg·m^2
Location of center of mass relative to geometrical center (x, y, z)	0.0023; 0.0034; 0.0025	m
Dimensions	0.1×0.1×0.1135	m

The positioning method is assumed to be realized by the reaction wheels [4], where the axis of rotation of each wheel corresponds to the axis of the satellite frame. The configuration of the reaction wheels relative to the satellite reference system is schematically presented in Figure 1.

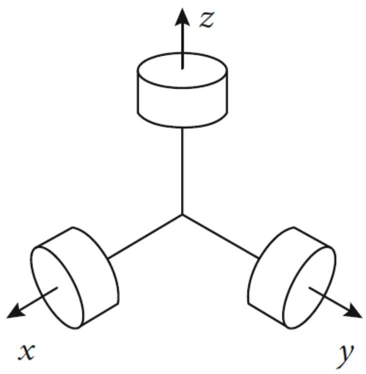

Figure 1. Diagram of the positioning of the reaction wheels in relation to the reference system of the satellite.

The characteristics of the reaction wheels together with the DC motor to which they are coupled are indicated in Table 2.

Table 2

Motor with reaction wheel characteristics

Description	Value	Unit
Moment of inertia about spin axis	1.25	kg·mm^2
Armature current	0.41	A
Speed	9000	min^{-1}

In any typical ADCS system, there are basically two parts: actuators (reaction wheels described above) and sensors. In case, studied in this paper, there are used the following sensors:

1. Microgyros - for determination of rotation velocity of the satellite.
2. Hall sensors - for determination of reaction wheel velocity.
3. Other IMUs for attitude determination.

3. Dynamics and kinematics of the satellite with reaction wheels

The equations that govern the attitude of a satellite can be represented by equations related to angular kinematics [5]. Knowing Euler's moment equation (1) [6]

$$\dot{h}_{tot} = N_e - \omega \times h_{tot}, \tag{1}$$

where $h_{tot} = \sum_j^N (\mathrm{I}_j\, \omega_j)$ is the sum of all parts (*N*) of the satellite, N_e is the total external impulse, ω angular velocity of the satellite.

The kinematics of the body is described by the attitude quaternion, in equation (2) below [6,7]

$$\dot{q} = \frac{1}{2}\Omega q \equiv \frac{1}{2}\begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix} q, \tag{2}$$

where and ω_1 is the rotation speed of the satellite relative to the *x*-axis, ω_2 relative to the *y*-axis and ω_3 respectively relative to the *z*-axis, *q* is the attitude quaternion. The attitude quaternion $\mathrm{q} = [q_1, q_2, q_3, q_4]^T$ is used to describe the kinematics of the satellite. The quaternion components are explicitly represented using Euler rotation angles in the sequence 3-1-3, the representation of quaternions by Euler angles is shown below [8].

$$q_1 = \cos(\varphi/2)\cos(\theta/2)\cos(\psi/2) - \sin(\varphi/2)\cos(\theta/2)\sin(\psi/2),$$
$$q_2 = \cos(\varphi/2)\sin(\theta/2)\cos(\psi/2) + \sin(\varphi/2)\sin(\theta/2)\sin(\psi/2),$$
$$q_3 = \cos(\varphi/2)\sin(\theta/2)\sin(\psi/2) - \sin(\varphi/2)\sin(\theta/2)\cos(\psi/2),$$
$$q_4 = \cos(\varphi/2)\cos(\theta/2)\sin(\psi/2) + \sin(\varphi/2)\cos(\theta/2)\cos(\psi/2).$$

The rotation of the satellite was further described using the rotation matrix [6], in which the elements of the attitude quaternion are used as parameters. Being known as I_S as the inertia matrix of the satellite, h_ω being the total angular momentum of the flywheels, *ω* as the angular velocity of the satellite, N_e as the total external impulse, all in the coordinate system attached to the satellite, the dynamics of the satellite is described by the following relations..

Thus, the dynamic equation is (3), or it can be written in the form (4):

$$\frac{d}{dt}(\mathrm{I}_S\,\omega) + \dot{\mathrm{h}}_\omega = N_e - \omega \times \mathrm{I}_S\,\omega - \omega \times \mathrm{h}_\omega, \tag{3}$$

$$\dot{\omega} = -\mathrm{I}_S^{-1}(\omega \times \mathrm{I}_S\,\omega) - \mathrm{I}_S^{-1}\,\omega \times \mathrm{h}_\omega - \mathrm{I}_S^{-1}\,\dot{\mathrm{h}}_\omega + \mathrm{I}_S^{-1}\,\mathrm{N}_e. \tag{4}$$

If the cross product is written as a matrix operation using $\mathrm{S}(\omega)$, then a simpler form is obtained (Equation (5))

$$\mathrm{S}(\omega) = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}, \tag{5}$$

is obtained (Equation (6)):

$$\dot{\omega} = -\mathrm{I}_S^{-1}\,\mathrm{S}(\omega)\,\mathrm{I}_S\,\omega - \mathrm{I}_S^{-1}\,\mathrm{S}(\omega)\mathrm{h}_\omega - \mathrm{I}_S^{-1}\,\dot{\mathrm{h}} + \mathrm{I}_S^{-1}\,\mathrm{N}_e. \tag{6}$$

The combined nonlinear dynamic model of the satellite is complemented by the fact that the control torque in the satellite coordinate system is N_c and provides a rate of change of the total angular momentum from the reaction wheels (Equation (7)):

$$\dot{h} = -N_C, \tag{7}$$

and therefore the dynamics of the satellite driven by the reaction wheels is described by equation (8)

$$\dot{\omega} = -\mathrm{I}_S^{-1}\,S(\omega)\,\mathrm{I}_S\,\omega - \mathrm{I}_S^{-1}\,S(\omega)h + \mathrm{I}_S^{-1}\,N_C + \mathrm{I}_S^{-1}\,N_e. \tag{8}$$

The satellite position is obtained by rotating the satellite frame with respect to the inertial frame by means of the matrix of director cosines A_{SI} [9]. The rotation matrix is parametrized by quaternions and denoted by $A_{SI}(q)$. The vector measured in the inertial frame is a_I, and the vector measured within the satellite frame has the coordinates a_S, so $\mathrm{a}_S = A_{SI}(q)\,\mathrm{a}_I$. The kinematics of the satellite is described by Equation (9)

$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix}. \tag{9}$$

For simplicity it will be represented as follows (Equation (10))

$$\dot{q} = \frac{1}{2}\Omega(\omega)q\,. \tag{10}$$

A For a later analysis, another detailed form of kinematics is considered. For this, Equation (9) is rewritten to a form that separates the terms containing q_4 from the other elements of the attitude quaternion. Thus the vector formed by the elements q_1, q_2, q_3 of the attitude quaternion is denoted by g.

$$\mathrm{g}=\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}.$$

Hence equation (10) takes the form (11-12)

$$\dot{\mathrm{g}} = -\frac{1}{2}\omega\times g + \frac{1}{2}q_4\omega\,, \tag{11}$$

$$\dot{q}_4 = -\frac{1}{2}\omega^T\mathrm{g}\,. \tag{12}$$

The full form of the model is (Equation (13))

$$\frac{d}{dt}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = -\frac{1}{2}\begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \\ \omega_1 & \omega_2 & \omega_3 \end{bmatrix}\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} + \frac{1}{2}\begin{bmatrix} q_4 & 0 & 0 \\ 0 & q_4 & 0 \\ 0 & 0 & q_4 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}. \tag{13}$$

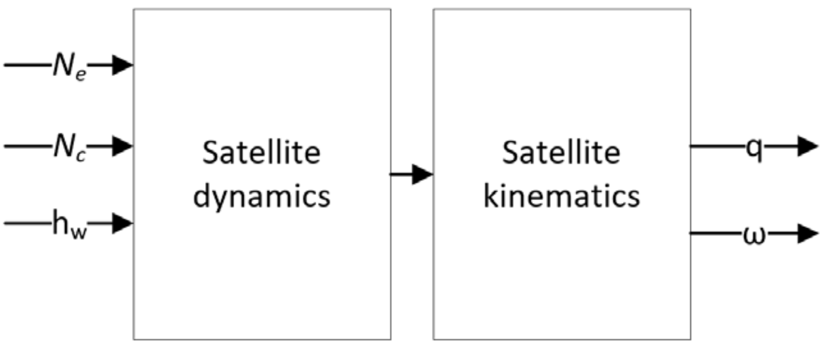

Figure 2. Satellite model with nonlinear dynamics and kinematics, where N_e - an external torque, N_c - control torque from reaction wheels, h_ω – angular momentum of wheels and output is q and ω.

So, it is obtained, that the kinematic equation is written using $q = \left[g^T, q_4\right]$, where g is the q_1, q_2, q_3 components of the quaternion (Eq. 14)

$$\frac{d}{dt}\begin{bmatrix} g \\ q_4 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} -S(\omega) \\ -\omega^T \end{bmatrix} g + \frac{1}{2} q_4 \begin{bmatrix} I_{3\times3} \\ 0 \end{bmatrix} \omega . \tag{14}$$

In this operation it preserves the unit length of the quaternion. The satellite model includes the dynamics in Equation (4) and the kinematics in Equation (10), that can be presented by the model presented in the Figure 2.

4. Attitude control system

The attitude control process is carried out according to the following scheme:

1. Only enabled with the permission of the mission planning process. As a rule, it will be requested at the moment of capturing the image and transmitting the data to the ground station.
2. It is checked if the stabilization and orientation of the satellite can be achieved, otherwise the process of combating hijacking/uncontrolled running will be activated.
3. The current attitude (current position) of the satellite will be determined.
4. The reference position of the nanosatellite will be obtained from the mission planning process or by telemetry command from the ground station (usually the requested position or "nadir" of the satellite).
5. The difference between the current position and the reference one is calculated and the error is transmitted to the controller.
6. Motors with reaction wheels shall be actuated according to the control law.
7. Steps 2-6 will be repeated, until the current position does not coincide with the reference one.

The orientation of the satellite is determined by interrogating the set of magnetometers, accelerometers, microgyroscopes and IGRF modeling (IGRF - International Geomagnetic Reference Field - the set of spherical harmonic coefficients, which can be entered into a mathematical model to describe the Earth's internal magnetic field).

The positioning of the nanosatellite is achieved by driving the reaction wheels, which are embedded on three axes *X*, *Y* and *Z*, which operate based on the principle of conservation of angular momentum. A reaction wheel is essentially a spinning wheel mounted on a satellite that can change its orientation by changing the speed and direction of the wheel's rotation. When a reaction wheel spins in one direction, the spacecraft will begin to rotate in the opposite direction, due to the conservation of angular momentum.

In this article, Figure 3 illustrates the overall design of a satellite attitude control system that was studied.

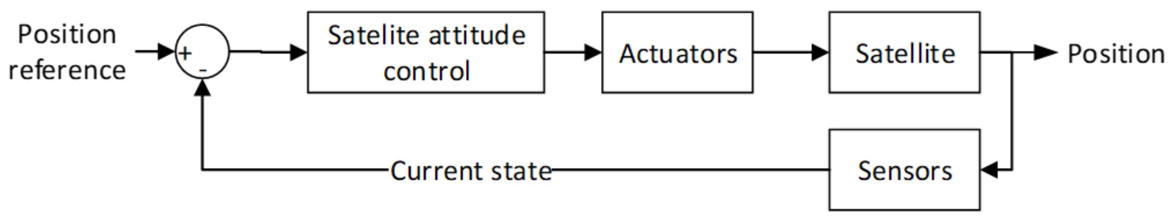

Figure 3. Design of a satellite attitude control system.

The simulation model utilized the models described earlier, namely the "Actuators" and "Satellite" blocks. However, the "Sensors" block was not included in this particular research. The "Current state" data block includes the state variables of the satellite, reaction wheels and the quaternion $q = [q_1, q_2, q_3, q_4]^T$.

5. Synthesis of the hybrid attitude control algorithm

The synthesis of a hybrid fuzzy PID control algorithm for satellite attitude control is an algorithm that combines the strengths of both fuzzy logic and proportional-integral-derivative (PID) control algorithm, to improve the performance of satellite attitude control. Fuzzy logic, which is based on fuzzy set theory, is well-suited for handling uncertainty and imprecision in the system and is effective in modeling complex and nonlinear systems.

On the other hand, PID control is a widely used as control algorithm, that is simple to implement and has good robustness and stability. By combining these two methods, a hybrid fuzzy PID control algorithm can achieve improved control accuracy and robustness over using either method alone. Synthesizing such a control algorithm is a challenging task that requires a deep understanding of the system dynamics and a combination of analytical and simulation-based approaches. It involves designing a fuzzy logic controller, a PID controller and then integrating them to achieve optimal control performance. This integration takes place using a set of instructions or functions, that set some rule to transmit the command from the PID or Fuzzy controller, or modify the command according to some function.

The PID control algorithm

The three parameters of the PID control algorithm are the proportional (P), integral (I), and derivative (D) components. The P component relies on the current error, the I component on the accumulated past error, and the D component on the anticipated future error, based on the current rate of error change, Figure 4 shows the block scheme of the automatic control system [10, 11].

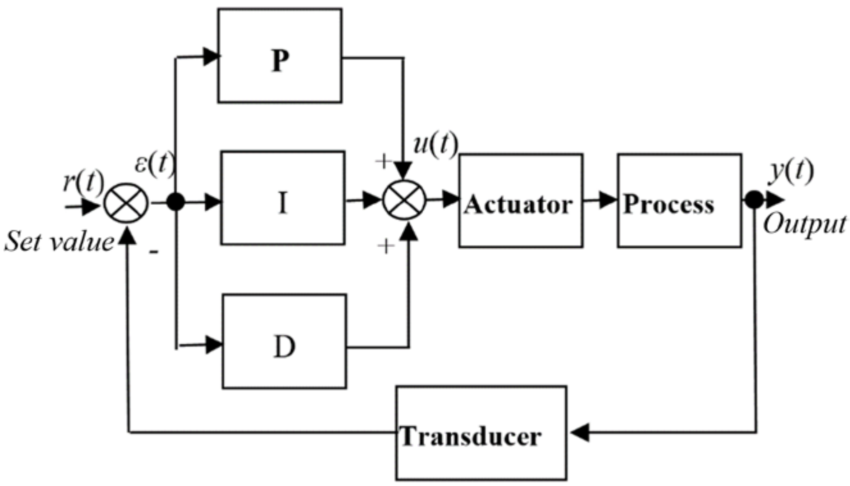

Figure 4. Block scheme of the automatic control system.

Various techniques exist for generating control algorithms, including experimental methods, graphic-analytical methods that rely on knowledge of the mathematical model approximating the process, optimization methods, and artificial intelligence approaches such as evolutionary algorithms, which are commonly employed in optimizing the PID control algorithm synthesis problem.

Fuzzy controller

Fuzzy Logic Control (FLC) is a type of control method that uses fuzzy set theory to represent data and interpret human experience in real-world scenarios. It operates based on a set of rules and has gained the attention of numerous researchers over the past few decades as an innovative and effective control approach for a variety of applications. One of the key advantages of FLC is its independence from the plant model, making it a popular choice for systems where the precise mathematical model of the object is unknown or contains significant nonlinearities. This characteristic has led to its widespread adoption and investigation [12].

The fuzzy controller is composed of the following three elements:

1. **Fuzzification stage:** the initial data is transformed into linguistic variables, where the values are determined based on the input membership functions. Specifically, for this paper, the input data for the Fuzzy Logic Controller (FLC) will consist of the error signal (e(t)) and the rate of change of the error signal (de/dt) [13]. The most commonly used input membership function to represent linguistic variables in this stage is the triangular membership function, but other types of membership functions can also be used, such as trapezoidal or gaussian. The linguistic variables can receive different values labeled as - Large Negative, Medium Negative, Small Negative, Zero, Small Positive, Medium Positive, Large Positive and labeled as (NB, NM, NS, Z, PS, PM, PB) respectively [14].
2. **Rule base:** the rule base is a method of decision-making that mimics the human thought process. It comprises the definitions of fuzzy membership functions allocated to each control variable, along with the essential rules that articulate the control's objectives through the use of linguistic variables. The rules are usually designed using natural language, making it easy for non-experts to understand and modify the controller. The rule base is a crucial component of the fuzzy controller, as it determines the behavior of the controller based on the input data.
3. **Defuzzification:** the decision deduced is converted back into numerical values. The input for defuzzification is the membership (certainty) in the implicit fuzzy sets resulting from the premise rules, and the output is a crisp number [15].

The membership functions for the input and output variables are presented in the Figure 5.

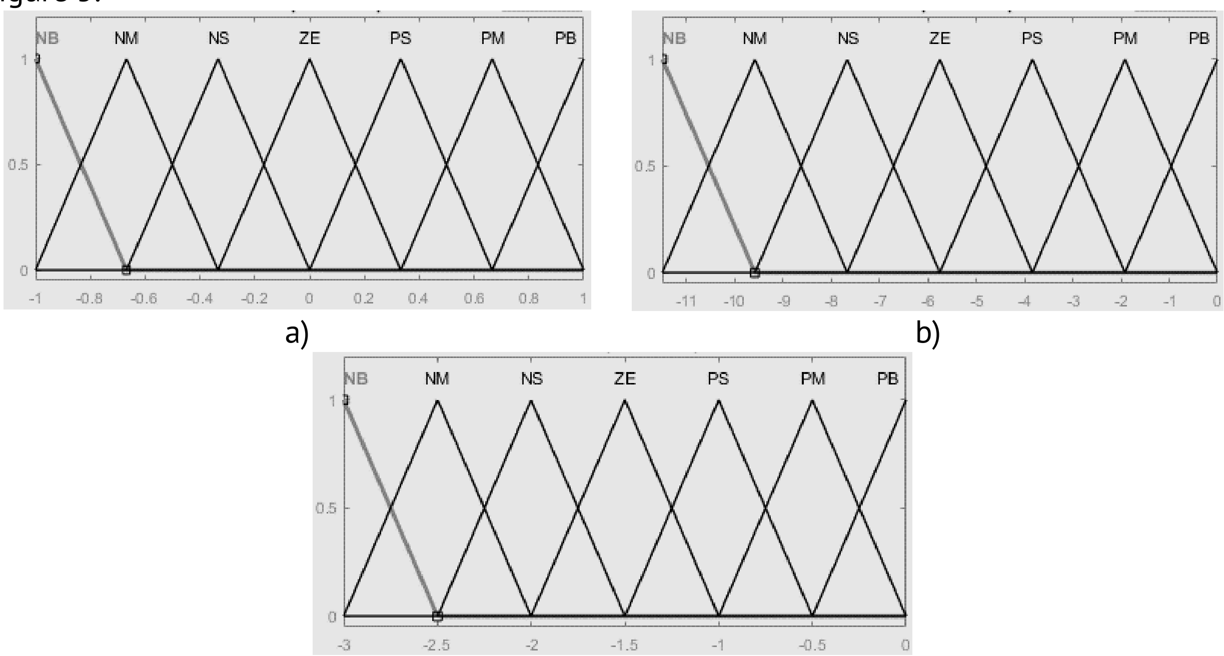

Figure 5. The membership functions: a) error signal;
b) rate of change of the error signal; c) command signal.

The fuzzy rules for the two input variables as: error signal - $e(t)$ and the variation of the error $\Delta e(t)$, based on which the attitude of the satellite is controlled are presented in Table 3.

Table 3

The base of the fuzzy rules

Δe(t) \ e(t)	NL	NM	NS	ZR	PS	PM	PL
NL	NL	NL	NL	NM	NS	ZR	PS
NM	NL	NL	NM	NS	ZR	PS	PM
NS	NL	NM	NS	ZR	PS	PM	PL
ZR	NM	NS	ZR	PS	PM	PL	PL
PS	NS	ZR	PS	PM	PL	PL	PL
PM	ZR	PS	PM	PL	PL	PL	PL
PL	PL	PL	PL	PL	PL	PL	PL

Note: NL-Large Negative, NM-Medium Negative, NS-Small Negative, ZR-Zero, PS-Small Positive, PM-Medium Positive, PL-Large Positive.

The Hybrid control algorithm

A hybrid fuzzy PID controller combines the concepts of fuzzy logic control and PID control to achieve better control performance in a system. The fuzzy logic component helps handle nonlinearities and uncertainties in the system, while the PID component provides robust and accurate control. the block diagram of the hybrid fuzzy PID controller is shown in Figure 6. It works in the following way: Fuzzy and PID controllers receive the error signal and perform some correction according to the control algorithm. After the correction performed at the output of the fuzzy and PID controllers, the signal is passed to the mixing block u_FUZZY and u_PID.

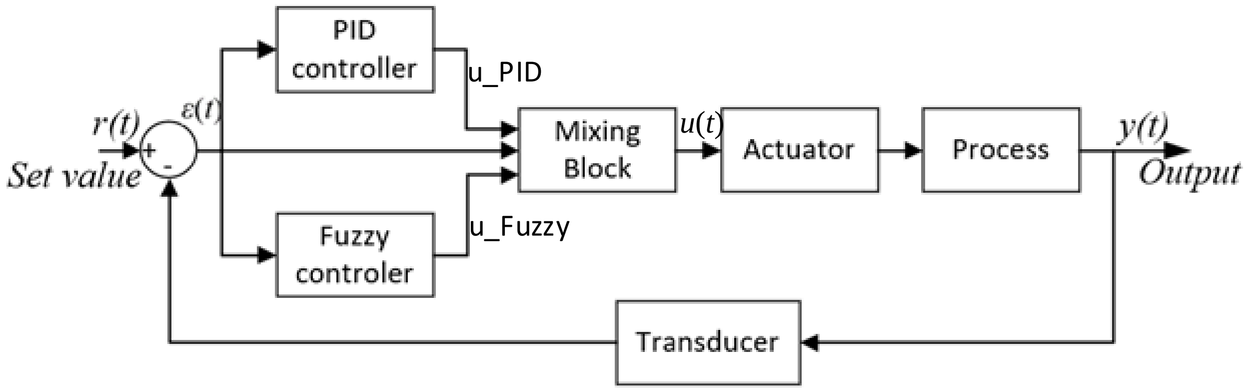

Figure 6. Control scheme of the hybrid controller.

The combination function is initially declared as a function with three inputs and one output, then a coefficient f is equal to the error value to the power of 2, $f(e) = e^2$, and the output variable is equal to 0.

Depending on the response of the Fuzzy controller and PID we have three cases:

1. If the response of the Fuzzy controller is faster than the response of the PID controller, then the command value *u* is calculated using the relation:
$$u_{hibrid} = f(e) * u_{PID} + \left(1 - f(e)\right) * u_{Fuzzy}$$
2. If the response of the PID controller is faster than the response of the Fuzzy controller, the command value *u* is calculated using the relation:
$$u_{hibrid} = (1 - f(e)) * u_{PID} + f(e) * u_{Fuzzy}$$
3. If the response of the PID controller is equal to the response of the Fuzzy controller, the command value u remains that of the PID controller.

6. Simulation

The hybrid fuzzy PID controller has undergone testing using a realistic simulation environment that incorporates a satellite model and attitude dynamics. This simulation was realized using the simulation software MATLAB/Simulink. The tool was utilized to construct the entire control loop and manage the integration of differential equations of continuous variables and output calculation of sensors. Customized attitude functions were also incorporated. The Simulink tool was employed to model the kinematics, mass properties, and motion of the satellite around its center of mass.

To control the rotations of the reaction wheels, the mathematical model of the reaction wheel engine was identified. The mathematical model of the direct current motor was experimentally identified using the System Identification Toolbox in Matlab. The identification process involved analyzing the experimental speed variation data of the DC motor at a reference speed of 7330 rpm.

The speed variation experimental data of the DC motor was modeled as a second-order inertial system [11]:

$$H(s) = \frac{k}{(T_1 s+1)(T_2 s+1)} = \frac{1.0069}{3.1695s^2+5.0289s+1}.$$

In this work, the Genetic Algorithm was used for the synthesis of the PID control algorithm for the speed control of the direct current motor (reaction wheels), depending on the imposed performance.

The PID control algorithm in the standard form was utilized, which is characterized by the following transfer function:

$$H_{PID}(s) = k_p + \frac{k_i}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s},$$

where k_p, k_i, k_d – are the tuning parameters of the PID control algorithm.

The PID controller was tuned by the genetic algorithm and there are obtained the following values of the tuning parameters: $k_p = 20.402$, $k_i = 4.58$, $k_d = 9.12$, It was obtained the transient response with following performance: t_r=0,55, t_s=2,00, σ=3,99, λ=*1,* [11].

The obtained simulation result of tuning the PID controller is presented in the Figure 7.

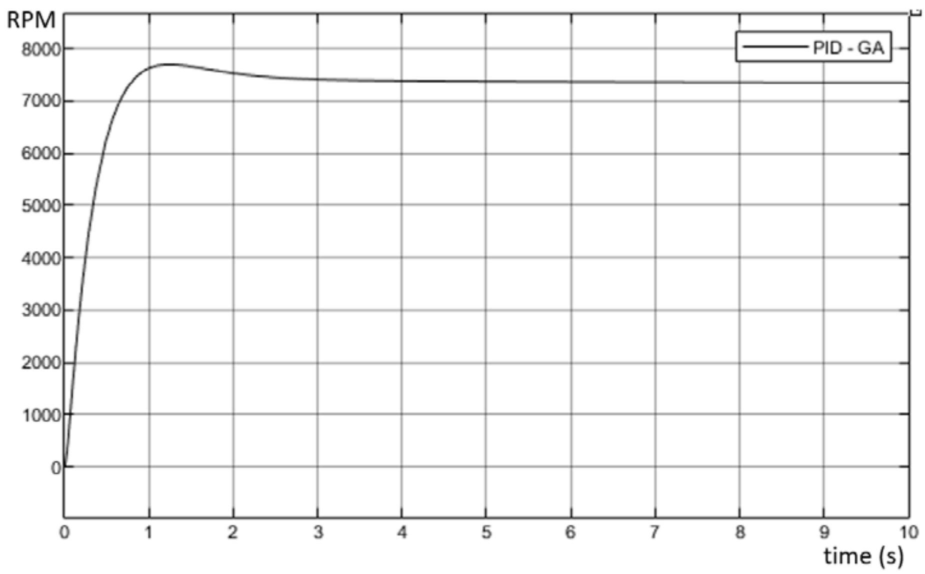

Figure 7. The transient responses of the control system with PID controller.

The transient responses of the satellite positioning control system using the PID control algorithm is presented in Figure 8. This algorithm ensures the settling time equal with 2.5 seconds.

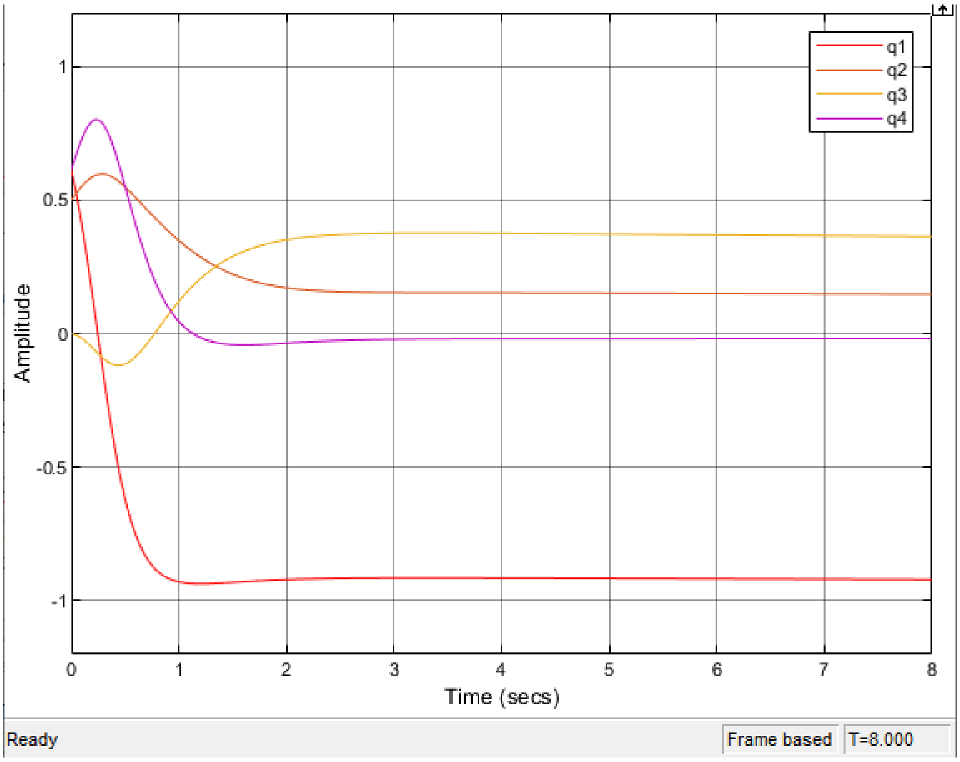

Figure 8. The transient responses of the control system with PID controller.

The transient responses of the satellite positioning control system using the hybrid fuzzy PID controller is presented in Figure 9. This algorithm ensures settling time equal with 2 seconds.

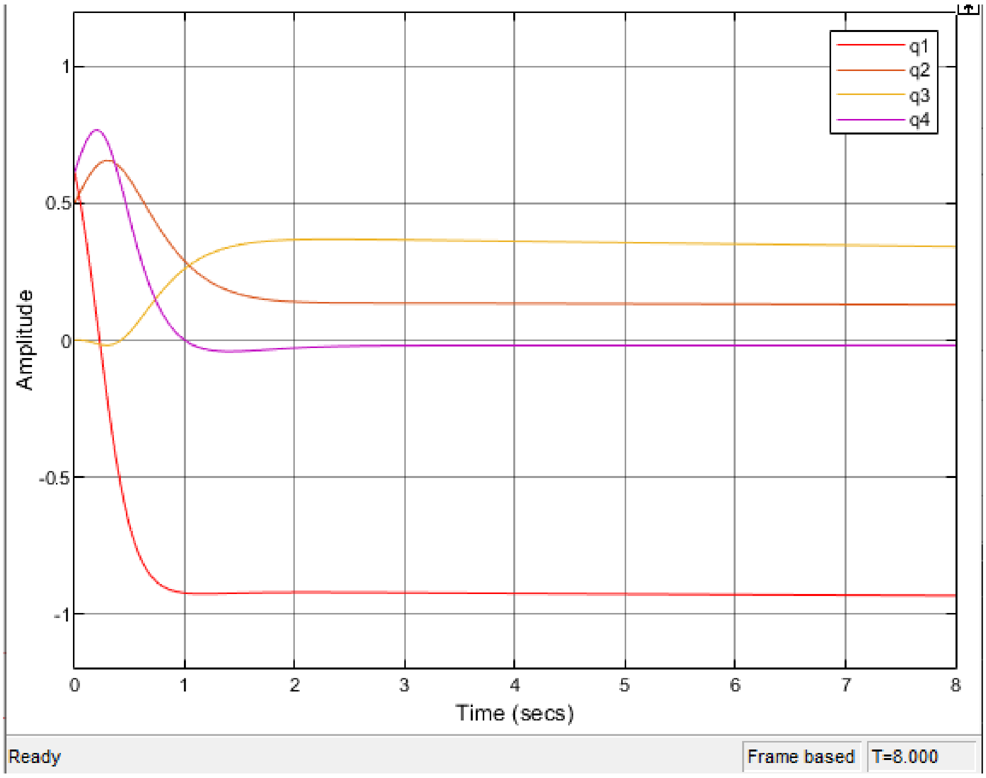

Figure 9. The transient responses of the control system with hybrid fuzzy PID controller.

From the simulation results, it can be observed, that using the hybrid fuzzy PID controller system has better performance than system with PID controller.

Conclusion

The paper compared the effectiveness of a hybrid fuzzy PID control algorithm with a classical PID control algorithm in process of controlling the attitude of a nanosatellite, by using a simulation of the system with a reaction wheels for positioning. Results indicated that artificial intelligence strategies, specifically fuzzy logic, could improve the attitude control of nanosatellites. The comparison also revealed that the hybrid fuzzy PID controller outperformed the PID controller in terms of settling time, with up to 20% faster. This is illustrated in Figure 10. Finally, the obtained results contribute to the development of an ADCS with 3 axes, which will also allow experimental testing of control algorithms.

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Conflicts of Interest: The author declares no conflict of interest.

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