2026 Volume: 02 Issue: 01 www.ijrpa.com ISSN 2456-9995 Research Article

International Journal Research Publication Analysis

Page: 01-14

ENHANCING THE DYNAMIC RESPONSE AND STABILITY OF MICROSATELLITE YAW-AXIS ATTITUDE USING AN INTELLIGENT-BASED CONTROL SYSTEM

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Article Received: 24 December 2025
Article Revised: 13 January 2026
Published on: 02 February 2026

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DOI: https://doi-doi.org/101555/ijrpa.5404

ABSTRACT

The significance of effective satellite attitude control system is that it can ensure both quality and reliability of data acquisition by a microsatellite. This work presents enhancing of the dynamic response and stability of microsatellite yaw-axis attitude using intelligent based control system. In order to achieve this, the transfer function models of amplifier, actuator, and satellite structure for determining the transfer function a microsatellite yaw-axis attitude were obtained. Then a composite controller based on the integration of fuzzy logic control (FLC) algorithm and proportional-derivative (PD) algorithm called Fuzzy-PD was developed. A MATLAB/Simulink model, which was computer-based model, was developed using the mathematical models of the closed-loop control system. The MATLAB/Simulink model was initially used to conduct computer simulation of microsatellite yaw-axis attitude control system without any controller. The result obtained in terms of response to unit step input in degree indicated a rise time of 1.89 s, settling time of 3.49 s and 0% overshoot. Thus, in terms of the performance criteria defined for the system, all conditions were not met specifically the settling time. Hence, with the developed Fuzzy-PD controller added to the closed-loop network of the ACS, simulation results revealed that the control system offered rise time of 0.7 s, settling time of 1.23 s, overshoot of 0%, and steady-state error 0. Generally, simulation results revealed that the Fuzzy-PD controller met all the performance criteria. When compared to other controllers, such as, PD, FLC, integral time absolute error (ITAE) based PID (ITAE-PID), ITAE PID plus pre-filter (ITAE-PIDf), ITAE-PD, and ITAE-PD plus pre-filter (ITAE-PDf) controllers, the developed system offered the best step response performance with respect to rise time (0.7s), and overshoot 0. The significance of this work is that a composite controller with intelligent based algorithm and classical PD has been developed and offered a more smooth and stable dynamic response advantage for the microsatellite yaw-axis ACS.

KEYWORDS: Fuzzy logic controller, microsatellite, Attitude control system, Fuzzy-PD, Proportional and derivative controller

1. INTRODUCTION

The critical demand for high-precision satellite attitude control is increasing, and the needs for reliable, stable and accurate satellite control system are becoming increasingly stringent considering the rapid development in aerospace industry (Shan *et al.,* 2022). The flight attitude of a satellite will change due to varying angular variations in pitch, yaw, and roll caused by gravitational perturbation and external disturbance during the on-orbit flight of the satellite. Considering, most specifically, the fact that some satellites have defined observation tasks, the slight change of attitude angle of satellite through the orbit radius enlargement with respect to the displacement deviation cannot be neglected. Since the performance of satellite tasks are directly determined by the control effect, it is of critical concern to investigate attitude control system and choose the control technique that will give better transient and steady-state performance for microsatellite.

Proportional Integral and Derivative (PID) controllers have been largely employed in many studies relating to control system and generally in several industrial process control operations because of its associated simple structure and design simplicity including the ability to provide control effort for system with complex dynamics. PID has been used in the control of many processes such as pitch control (Okeya *et* al., 2024), for hard disk drive (HDD) positioning system (Onyekwelu *et* al., 2023), in turning of compensator for robust transient response in engine's idle speed control (Eze *et al*., 2017), to improve the response of two-phase hybrid stepper motor based control system (Onyeka *et al*., 2019; Muoghalu & Achebe, 2021), enhancing the performance of chopper fed DC motor speed control (Muoghalu *et al.*, 2021), in human heart stabilisation system (Muoghalu *et al.*, 2024), combined with LQR in temperature control system, and positioning and tracking in robot manipulator (Ekengwu *et* al., 2024; Okafor *et al*, 2025), linear wheel slip control in antilock braking system (ABS) (Eze *et al.,* 2018; Ekengwu *et al.*, 2018), and for positioning control in electrical discharge machine (Eze *et* al., 2017). It has also been widely implemented in satellite Attitude Determination Control System (ADCS) (Benzeniar & Fellah, 2014), including with adaptive features as Adaptive PD (ADP)used yaw-axis stabilization in Achebe and Muoghalu (2025). For instance, PID has been advantageously considered for satellite yaw-axis ACS because of its rapid transient response and zero steady-state error (Hassan, 2009). Despite the advantages of classical PID controllers, their performances are largely affected by mismatch or parameter variation (Agwah & Eze, 2022). In nanosatellite ACS, PID controllers shown weakness of relatively long area of little variation phase prior to correcting the final sate in some maneuvers and was unable to stabilize LEO satellite attitude after 500 s which is beyond allowable practical value (Bello et al., 2023; Enejor *et al*., 2023). Intelligent based control such as FLC and fuzzy-PID have been proposed to replace PID controllers. This can be attributed to the fact that heuristic information is used by FLC to offer realistic and expedient alternative to addressing nonlinear problems related to control systems (Eze *et al.*, 2021a). However, the use of FLC controller only results in steady-state error (Agwah & Eze, 2022; Eze & Ezenugu, 2024; Ekengwu *et al.*, 2024) while expert PID and fuzzy-PID controllers on the other hands, always have sub-par timing precision and limited anti-interference capabilities (Liu *et al.*, 2023). Even though CMGs are satellite attitude control actuators that act as torque amplifier and suitable for three-axis slew maneuvering, the drawback of the scheme is the possibility of singularities for certain gimbal angles combination (Si Mohammed, 2012). LQR and LQG controllers have the ability to provide optimal control to system performance with improved settling time and almost zero overshoot (or oscillation), but their feat degrades because of nonlinearity and delay as the system reaches the setpoint (Eze *et al.*, 2021b). Adaptive PID controller was shown to eliminate oscillatory actions of PID which was due to initial overshoot and as such, the convergence time of the PID was significantly minimized for nanosatellite ACS (Bello *et al.*, 2023). Hence, taking into account the advantage of adaptive PID controller, an adaptive controller is proposed in this paper for microsatellite yaw-axis ACS.

Generally, in linear or classical PID controller application, the performance of the control system is usually influenced by dynamic mismatch and distortion in parameter. Nevertheless, the use of intelligent based control method can overcome the effect of unknown model uncertainties such as variation in system parameter. Contrary to PID controller, whose control is only governed by the value of actual output of the system based on feedback mechanism, fuzzy is governed the dynamic behaviour of at least two input variables. In this work, the error and change in error are the two input variables. Generally, the PD controller which offered the best performance for the considered microsatellite as recommended by Ajiboye *et al.* (2020) has disadvantages of low convergence time, relatively low anti-perturbation capability, and sensitivity to disturbance torques. The first problem can be addressed by increased gains of the PD parameters, which exacerbate to the second disadvantage. Thus, the inclusion of fuzzy with the PD can address the second problem.

2. METHODS

In this section the description of a microsatellite is presented in terms of attitude closed loop control network. Furthermore, the performance criteria of the system are established in terms of overshoot, settling time, and steady state error.

2.1 Proposed System and Description

The proposed intelligent based control system for yaw-axis attitude is shown in Figure 1. The closed loop description of a microsatellite yaw-axis ACS studied in Ajiboye et al. (2020) is shown in Figure 2. It is a Single Input Single Output (SISO) linear time-invariant (LTI) system with unity feedback gain. With the block diagram arrangement, the microsatellite yaw-axis ACS can be vividly described in very simplified manner. Thus, as shown in Figure 2, during the on-orbit flight of the satellite, an attitude maneuver takes place which involves the controller sending a control signal to the amplifier in order to boost the signal strength (via increase in magnitude) and the amplified signal (which is the motor armature voltage) reaches the actuator (motor) that produces a proportional output that is sufficient enough to adjust the satellite structure (plant) orientation in terms of yaw angle in this case according to the error signal (which is the difference between the desired (target) attitude and the actual attitude measured by the feedback sensor. Generally, the attitude controller is designed to align the actual attitude (yaw angle) to a desired attitude (or target angle). The desired attitude can be pointing in fixed direction (that is static orientation) or dynamic with respect to time (Bello et al., 2023).

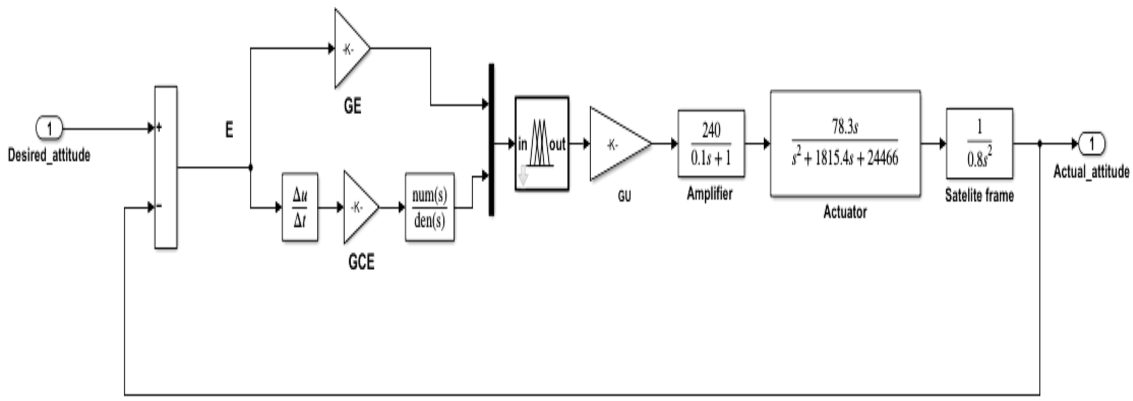

Figure 1 Proposed fuzzy-PD controller for microsatellite yaw-axis ACS.

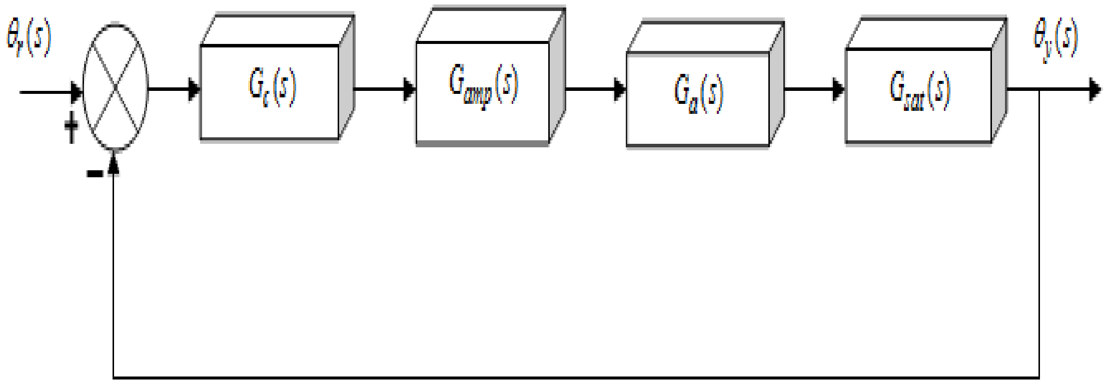

Figure 2: Block diagram of attitude control loop.

The dynamics of the amplifier, actuator and the satellite structure are determined in terms of transfer functions in Laplace form (s-domain) given by Ajiboye et al. (2020):

$$G_{sat}(s) = \frac{1}{0.8s^2} \quad (1)$$

$$G_a(s) = \frac{78.3s}{s^2 + 1815.4s + 24466} \quad (2)$$

$$G_{amp}(s) = \frac{240}{0.1s + 1} \quad (3)$$

where $G_{sat}(s)$ is the satellite structure (plant) dynamic, $G_a(s)$ is the actuator dynamic, and $G_{amp}(s)$ is the amplifier dynamic.

Performance Criteria

The objective is to design a Fuzzy-PD controller to meet the following tracking specifications expressed as maximum overshoot ($M_p \leq 5\%$), settling time ($t_s \leq 2\,s$) with 2% criterion, zero steady-state error for a microsatellite yaw angle control system.

2.2 Controller Design

In this subsection, the approaches to design and subsequent implementation of the proposed intelligent based technique called fuzzy logic with proportional and derivative (Fuzzy-PD) controller are presented.

Fuzzy Logic Control Design

Table 1 and are defined as follows: Negative Large (NL), Negative Medium (NM), Negative (NE), Zero (ZE), Positive Large (PL), Positive Medium (PM), and Positive (PO). There are three Membership Functions (MFs) for each input and five MFs for the output. The total number of formulated rules for the designed FLC is nine.

Table 1 Rule table of fuzzy logic.

E/CE	NE	ZE	PO
NE	NL	NM	ZE
ZE	NM	ZE	PM
PO	ZE	PM	PL

Each input MF is graded as follows: NE = [-2 -1 0], ZE = [-1 0 1], and PO = [0 1 2]. For the output, each MF is sorted as: NB = [-1 -0.75 -0.5], NM = [-0.75 -0.5 -0.25], ZE = [-0.25 0 0.25], PM = [0.25 0.5 0.75], and PB = [0.5 0.75 1]. The inputs and the output were modelled by using triangular MFs.

Proportional and Derivative Control Design

The PD controller comprises proportional and derivative gains. The PD was designed in this work using the PID-tuner of the MATLAB/Simulink. The block diagram of PD control system for the microsatellite yaw-axis attitude is shown in Figure 3. The mathematical expression for the PD controller is defined by Equation (4).

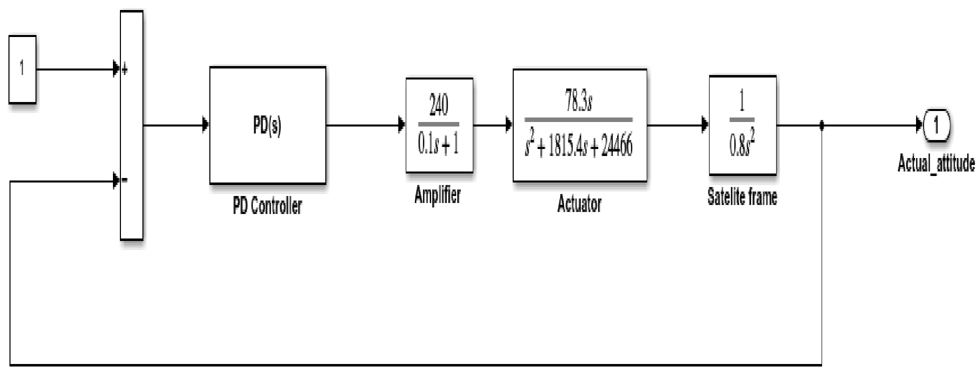

Figure 3: Simulink model of the PD control system.

$$G_{PD}(s) = K_P + K_D s \quad (4)$$

The PD is cascaded with the microsatellite yaw-axis attitude dynamics in Simulink as shown in Figure 3. This results in closed-loop transfer function given in Equation (5). With Equation (5), the PD parameters were obtained via tuning. Table 2 shows the value of PD parameters.

$$\frac{\theta_o(s)}{\theta_d(s)} = \frac{G_{PD}(s) \times G_{amp}(s) \times G_a(s) \times G_{sat}(s)}{1 + G_{PD}(s) \times G_{amp}(s) \times G_a(s) \times G_{sat}(s)} \quad (5)$$

Table 2 Tuned Parameters and Performance of the designed PID.

PID parameters	Value
Proportional gain, K_P	7.0716
Derivative gain, K_D	0.8041

3.3.2 Design of Fuzzy-PD

Now, the PD was introduced into the simplified closed loop structure of the FLC system in Figure 3.4. The tuned parameters of the designed PD were modified as in Equation (3.10) and combined with the FLC algorithm in Simulink.

$$\left. \begin{aligned} K'_P &= 1 \\ K'_D &= \frac{K_D}{K_P} = 0.1137 \end{aligned} \right\} \quad (6)$$

The product of error E with the new proportional gain, K'_P, is represented by GE, and the product of the change or derivative of the error CE with the new derivative gain, K'_D, is represented by GCE. The product of the output U of the fuzzy with an optimally selected gain corresponding to the initial proportional gain K_P = 7.0716, represents the GU as shown in the block diagram of the proposed system in Figure 1.

3. RESULTS AND DISCUSSION

This section presents the results of the simulation analysis conducted in MATLAB/Simulink environment to investigate the performance of the designed Fuzzy-PD controller in terms of time domain transient response characteristics. There are three subsections considered in this section to clearly analyze and discuss the obtained simulation results. These subsections are simulation analysis of the conventional system based on direct or proportional control provided by the amplifier (i.e. conventional system), simulation analysis of Fuzzy-PD control system, and simulation comparison of proposed system with other previously implemented control systems. The effectiveness of the control system is considered to be its ability to maintain or track a desired satellite yaw axis attitude which is taken in this work as unit step input in degree while at the same time meeting the performance specifications.

3.1 Simulation Analysis of System without Controller

In this scenario, simulation analysis was conducted to investigate the performance of the microsatellite yaw axis attitude in the absence of a controller. That is no controller was introduced as a subsystem in the attitude control system (ACS) so as to ensure the stabilization of the satellite yaw angle and tracked the desired yaw-axis attitude while ensuring that the system performance criteria that include rapid convergence (that is reaching steady state as fast as possible, which is defined by the settling time in second) with little or no cycling (defined in terms of peak overshoot in percentage) are met. The resulting step response of uncompensated satellite yaw-axis ACS is shown in Figure 4. The numerical analysis of the step response curve is shown in Table 3.

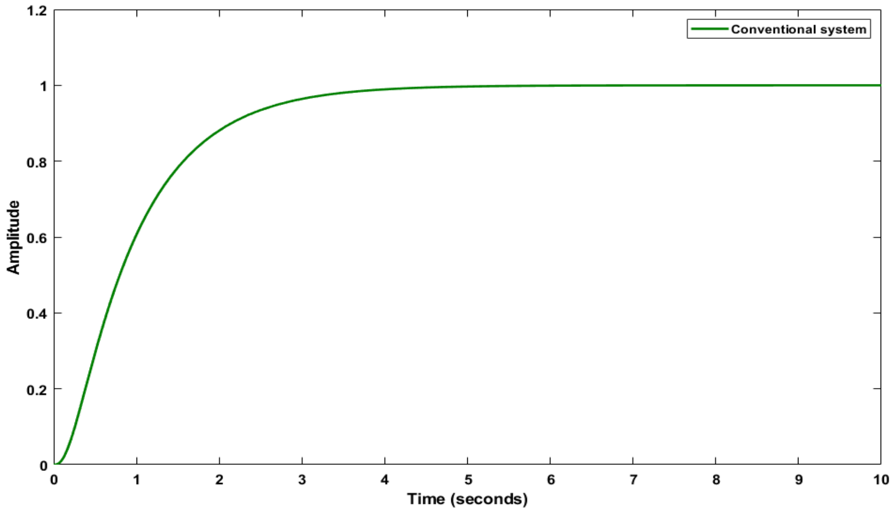

Figure 4: Step response of system without controller.

Table 3 Time domain characteristics of system without controller.

Step response parameter	value
Rise time	1.89 s
Transient time	3.49 s
Settling time	3.49 s
Peak overshoot	0
Steady state error	0

Considering the step response shown in Figure 4, the numerical analysis as shown in Table 3 revealed that in the absence of a control algorithm, the system has a transient and steady-state that is characterized by rise time of 1.89 s, transient time and settling time 3.49 s respectively, peak overshoot of 0, peak time of 10 s, final value of 1 degree, and steady state error of 0. As shown in the figure, the curve revealed that in the absence of a controller, the system response appears to be slow given the rise time and the fact that the system was not able to achieve the desired attitude at the predetermined convergence time (that is the stated settling time defined as the system performance criteria). Thus, there is need to design a controller for on-orbit flight performance improvement in terms of yaw angle.

3.2 Simulation Analysis of Fuzzy-PD Control System

The simulation results are presented in this section in terms of the microsatellite yaw-axis attitude with the Fuzzy-PD controller in this work. The step response of the Fuzzy-PID control system is shown in Figure 5. The numerical analysis of the step response plots in terms of transient and steady state is listed in Table 4.

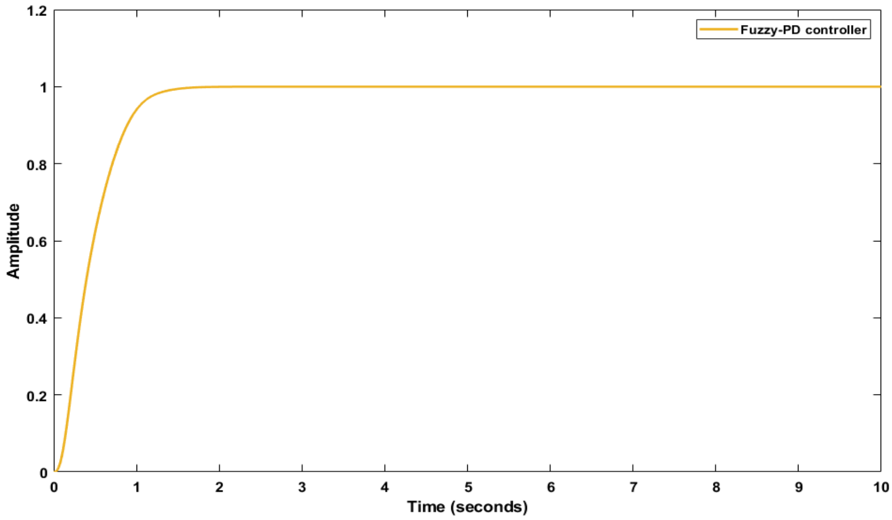

Figure 5: Step response of system with Fuzzy-PD control system.

Table 4. Time domain characteristics of system with Fuzzy-PD controller.

Step response parameter	value
Rise time	0.7 s
Transient time	1.23s
Settling time	1.23 s
Peak overshoot	0%
Steady state error	0

Looking at Table 4.4, it can be observed that the Fuzzy-PD control system meets all the performance criteria of the design measured in terms of settling time of less than or equal to 2 s, peak overshoot of less than or equal to 5% with 2% criterion and zero steady state error. Thus, the designed intelligent based system, which was developed from the combination of FLC (intelligent algorithm) and conventional PD, met the stated performance or design specifications.

3.3 Simulation Analysis for Control System Comparison

In order to ascertain the effectiveness of the proposed controller over previously applied control techniques by Ajiboye et al. (2020) on the microsatellite yaw axis ACS considered in this work, comparison was done via simulation. The simulation curves of the various control systems and the numerical analysis of the plots are shown in Figure 6 and Table 5. The previous control systems were integral time absolute error (ITAE) based PID controller, ITAE based PID with pre-filter (PIDf), ITAE based PD, and ITAE based PD with pre-filter.

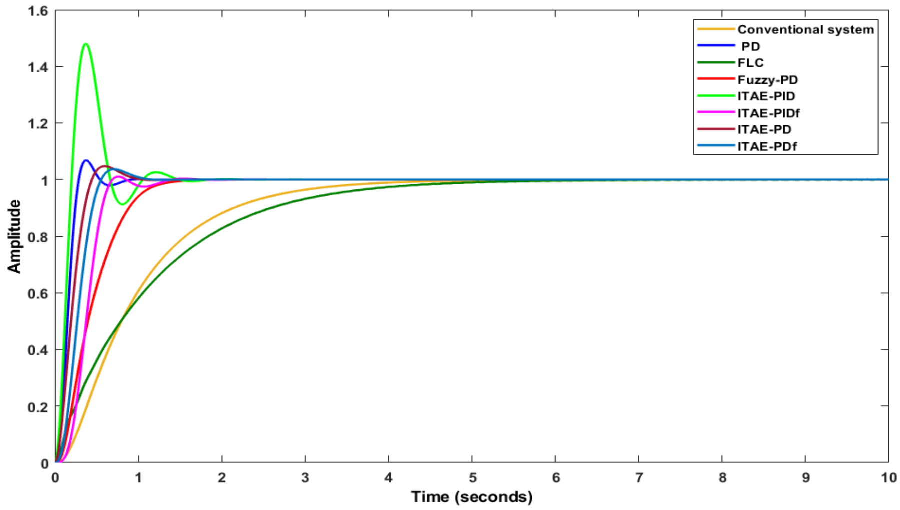

Figure 6: Step response comparison for different control systems.

Table 5 Step response performance comparison of different control techniques

System condition	Rise time (s)	Transient time (s)	Settling time (s)	Overshoot (%)	Steady-state error
Conventional system	1.89	3.49	3.49	0	0
PD	0.18	0.69	0.69	6.84	0
FLC	2.48	4.29	4.29	0	0
Fuzzy-PD	0.7	1.23	1.23	0	0
ITAE-PID	0.14	1.30	1.30	47.8	0
ITAE-PIDf	0.37	1.17	1.17	0.92	0
ITAE-PD	0.29	0.82	0.82	4.67	0
ITAE-PDf	0.33	0.67	0.67	3.59	0

From Figure 6 and Table 5, it can be deduced that all the expected performance criteria were not met by the conventional system, FLC, PD, and ITAE-PID controllers. The worst performance in terms of high frequency oscillation in response was exhibited by the ITAE-PID with an overshoot of 47.8%. Nevertheless, the proposed Fuzzy-PD, IATE-PIDf, ITAE-PD, and ITAE-PIDf achieved the required design performance specifications. It can be seen from the table that among the control systems that met all the requirements, the control torque or signal of the proposed Fuzzy-PD controller offered no overshoot amongst all the control systems that satisfied the design specifications. Therefore, the proposed system met the design requirement and offered the smoothest and most stable dynamic response compared to the previously implemented control systems for the considered microsatellite yaw-axis ACS.

4. CONCLUSION

This work has presented enhancing the dynamic response and stability of microsatellite yaw-axis attitude using intelligent based control system. In order to realize the aim of this work, the dynamic equations representing the behaviour of a microsatellite yaw-axis in attitude control system were determined. The dynamic equations were then modelled using Simulink embedded blocks in MATLAB. An intelligent based control system was developed by hybrid combination of fuzzy logic and proportional and derivative algorithms to effectively provide command action for microsatellite yaw-axis ACS. The proposed control system was modelled and simulated in MATLAB/Simulink environment. The developed Fuzzy-PD controller offered provided efficient and smooth control process for yaw-axis ACS. The results from the simulation revealed that the proposed controller met the performance specifications of the microsatellite yaw-axis ACS. The system performance was measured in terms of time domain transient characteristics such as rise time, transient time, settling time, maximum overshoot, peak time, final value and steady state error. The effectiveness of the proposed system was further examined by comparing it with existing strategies. It was observed that among the designed control systems simulated, the FLC and Fuzzy-PD control systems offered smooth response with zero overshoot. However, the proposed Fuzzy-PD controller outperformed all the other control system by not just only meeting the design performance criteria but also providing finest response with improved stability.

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