International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 21, Issue 2 (February 2025), PP 225-232

Design of Adaptive PD Controller for Microsatellite Yaw-Axis Attitude Control System

*Achebe, P. N., Muoghalu, C. N.
Department of Electrical and Electronic Engineering, ChukwuemekaOdumegwuOjukwu University, Uli, Nigeria
**Corresponding Author*

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 paper presents design of Adaptive Proportional and Derivative (APD) controller for microsatellite y-axis attitude control system (ACS).The transfer function models of amplifier, actuator, and satellite structure for microsatellite yaw-axis attitude were obtained. An APD was designed as a Simulink model. Initial computer simulation of the microsatellite yaw-axis attitude control system was carried out without any controller. The response dynamic characteristic to unit step input indicated a rise time of 1.89s, settling time of 3.49 s, and 0% peak overshoot. These parameters indicated that the performance criteria defined for the system, all conditions were not met precisely the settling time.. Hence, an APD controller was designed and introduced into the system, which resulted in a system with improved performance and which also met all the designed criteria. The simulation analysis revealed that the proposed APD improved the transient and steady-state performances of the system with rise time of 0.99 s, settling time of 1.71 s, peak overshoot of 0%, and steady-state error 0. Hence, the designed APD controller met all the performance criteria.When compared to the classical PID, PID with Pre-filter (PIDF), Proportional Derivative (PD) and PD with Pre-filter (PDF) controllers, the APD system provided the best step response performance with respect to smoothness and stability during control process.

Keywords: *Adaptive PD, Attitude Control System, Controller, Microsatellite, Yaw-axis*

Date of Submission: 07-02-2025 Date of acceptance: 18-02-2025

I. INTRODUCTION

Attitude in relation to spacecraft communication means to satellite’s orientation in space. Attitude control can be defined as the control of the orientation axis of an on-orbit flight satellite. An on-orbit flight satellite is one that is orbiting in space. Therefore, attitude control system (ACS) consists of set of components forming a system (with controller inclusive, which is a subsystem) that aids in analyzing and control of satellite orientation in space. The main task involve in attitude control is to enable the accurate pointing of satellite antenna at a particular region of interest on the ground-based stations and solar panels towards the direction of the sun.

In carrying out attitude control, the method of adding a potential detector is relatively important. This method involves the use of infrared sensors to enable the detection of the earth’s circumference relatively to background of the space. In this approach, four sensors are incorporated such that a quadrant is covered by each while the centre of the earth is made the point of reference. Hence, one or more sensor detects the changes in satellite orientation and subsequently, a restoring torque corresponding to the detected change is generated by the system. Control signals can be sent from ground stations with respect to the attitude information received from the space orbiting satellite despite the fact that changes in take place in the space region of the satellite. At any time the attitude is altered, the control signals are sent from the ground station to implement attitude maneuvers.

The following are ways of generating the torque that controls the attitude and are: passive attitude control and active attitude control. In the passive attitude control, the control system action is rather similar to that of open loop control system. This allows the satellite to maintain the referenced attitude such that its position is kept using little torque or in some cases at no torque. The satellite is stabilized by this method without impeding satellite energy supplies. Examples of passive attitude control are: gravity gradient stabilization, spin stabilization, and dampers. For the second method, active attitude control, the control action is considered that of a closed loop control system, which requires a feedback to ensure necessary adjustments are made. In contrary to the passive attitude control, which does not provide the overall torque for stabilization to compensate for disturbance torques; the active attitude control produces the overall corrective torques required to adequately address the effect of disturbance torques.

In feedback control system for satellite attitude, the method commonly used is the classical PID controller. This is because its design and implementation seems to be easy and simple [1,2]. This advantage has made PID control the most common choice of control in attitude and position control systems. However, classical PID controllers are usually prone to parameter variation and nonlinearity effect including high overshoot and as such, they have been replaced, integrated with other control algorithms or modified by tuning it parameters with intelligent algorithm in many feedback control loops. For instance, [3] used linear quadratic regulator (LQR) to improve the transient response of robot grinding system for efficient speed and positioning. In a feedback control system for satellite antenna systems, positioning was achieved by substituting digital cascaded compensator and model predictive control (MPC), separately for PID in [4] and [5]. Also, PID was integrated separately with LQR and model reference adaptive control (MRAC) to improve the performance of feedback control loop for temperature in refrigeration system and antilock braking system, respectively [6] and [7].Furthermore, to enhance classical PID controller, its parameters were optimized using back propagation neural network position control of dish antenna [8].

In satellite ACS, need for high-precision with more reliable, stable and accurate system performance, has resulted in the development of control strategy that serves as subsystem to provide needed maneuvering capacity to keep the satellite in its defined orientation for effective flight operation. Some of the controllers that have been developed in recent past are briefly highlighted. Integral Time Absolute Error (ITAE) based PID controller and Proportional and Derivative (PD) controller have been used for stabilizing attitude motion for microsatellite yaw-axis [9]. The kinematic model and dynamic model of satellite attitude was used in the design of satellite attitude controller (SAC) based on PID control system and fuzzy-PID based control system [10]. The performance of laboratory nanosatellite and its testing system in terms of energy consumption, convergence time and robustness in accordance to changes in environmental condition, which were the performance criteria including steady state error (accuracy) was examined using fuzzy Logic Controller (FLC), conventional PID controller, and adaptive PID controller that uses logic blocks that resets (or zeroes) the integral element whenever change of sign in error function occurs [11]. Selectable gains PID controllers were used for a generic model of a nanosatellite attitude control and stabilization system [12].Performancecomparison of PID control system and Linear Quadratic Regulator (LQR) for on-orbit stabilization of a Low Earth Orbit (LEO) satellite [13]. An MRAC augmented PID was used to improve the dynamic response of microsatellite yaw-axis ACS in [14].

Though the classical PID has its shortcomings, its algorithms can be modified to address its challenges such as high overshoot and influence of parameter variation. Hence, in this paper, an Adaptive PD (APD) controller was developed in MATLAB/Simulink to provide feedback control for yaw-axis of microsatellite.

II. SYSTEM DESIGN

This section presents the description of the microsatellite in terms of the mathematical equations and closed loop network of yaw-axis. Furthermore, the performance criteria of the system are established in terms of overshoot, settling time, and steady state error. Figure 1 shows the closed loop control system for the microsatellite yaw-axis with adaptive PD controller. It is a single input and single output (SISO) linear time invariant (LTI) system.

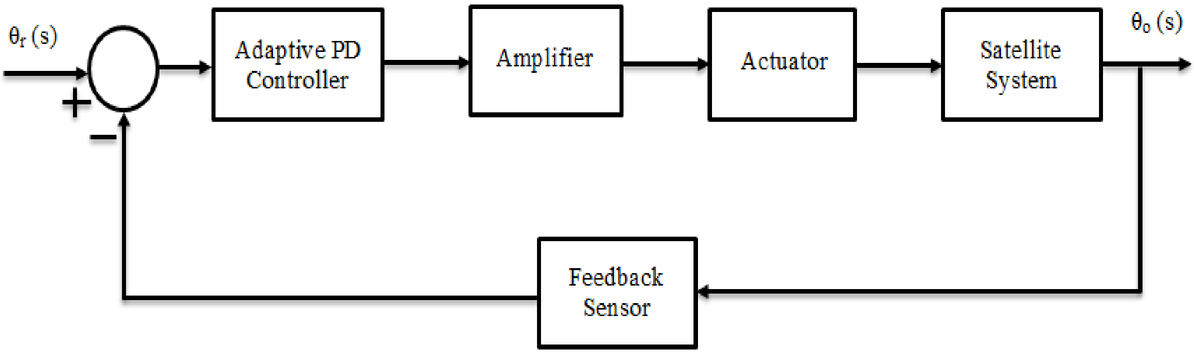

Figure 1: Yaw-axis ACS for microsatellite with adaptive PD controller

The mathematical expression for the amplifier, actuator and the satellite structure are established in terms of transfer functions in Laplace form (s-domain) given by [9,14]:

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

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

$$G_{sat}(s) = \frac{1}{0.8\,s^2} \tag{3}$$

where $G_{amp}(s)$ is the amplifier dynamic, $G_a(s)$ is the actuator dynamic, and $G_{sat}(s)$ is the satellite structure (plant). From Figure 1, the closed loop transfer function of the system without the controller is given by:

$$\frac{\theta_o(s)}{\theta_r(s)} = \frac{18792s}{0.08s^5 + 146s^4 + 3410s^3 + 1.957\times10^4 s^2 + 18792s} \tag{4}$$

The control objective is to design an adaptive PD controller to meet the following tracking specifications expressed as maximum overshoot ($M_p \le 5\%$), settling time ($t_s \le 2\,\mathbf{s}$) with 2% criterion, zero steady-state error for a microsatellite yaw angle control system. The structure of proposed adaptive PD controller developed with MATLAB/Simulink is shown in Figure 2 and the Simulink Block diagram of the closed loop system is shown in Figure 3.

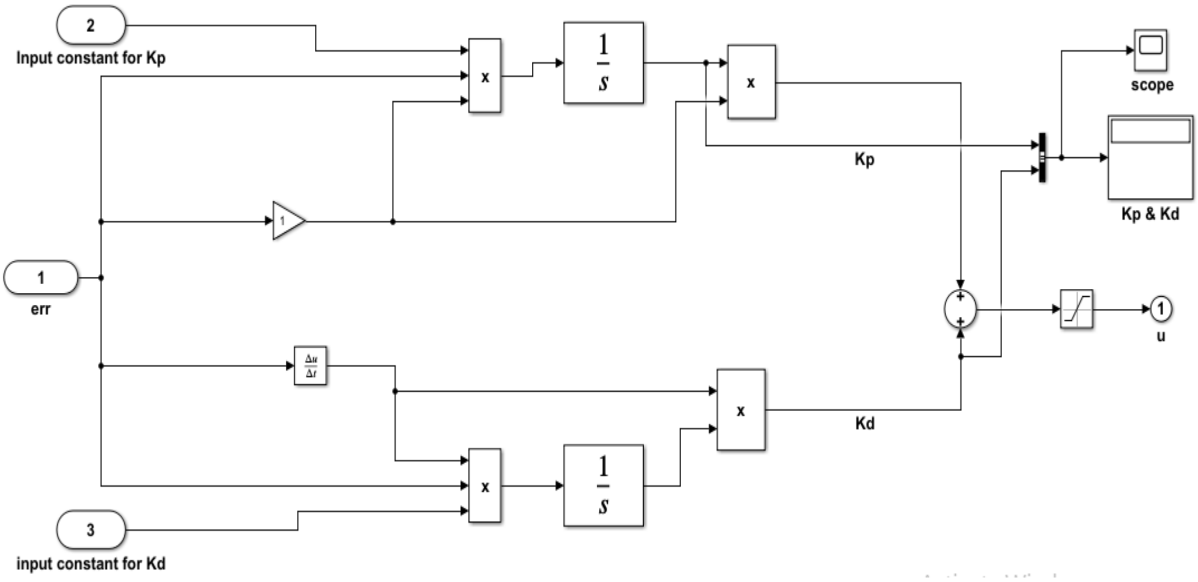

Figure 2: Simulink model of Adaptive PD controller

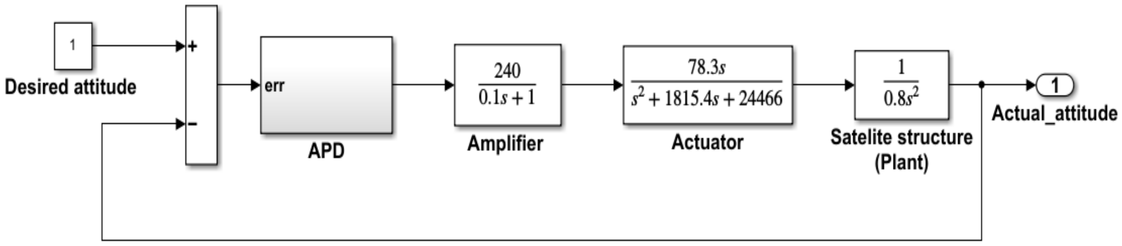

Figure 3: Simulink model of closed loop control system

III. RESULTS AND DISCUSSION

This section presents the results of the simulation analysis conducted in MATLAB/Simulink environment to investigate the performance of the designed APID control system for satellite yaw-axis attitude 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 sections are simulation analysis of system without controller, simulation analysis of APID controller, and simulation comparison of proposed system with other 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 of the design.

3.1 Analysis of System without Controller

The performance of the microsatellite yaw axis attitude in the absence of a controller is considered in this subsection. In this case, no subsystem or unit was introduced into the yaw-axis ACS loop of the microsatellite in order to ensure that the yaw angle is stabilized and the system maintains the design criteria. The actual yaw-axis attitude achieved in this control condition is shown in Figure 4. The numerical analysis of the step response curve is shown in Table 1.

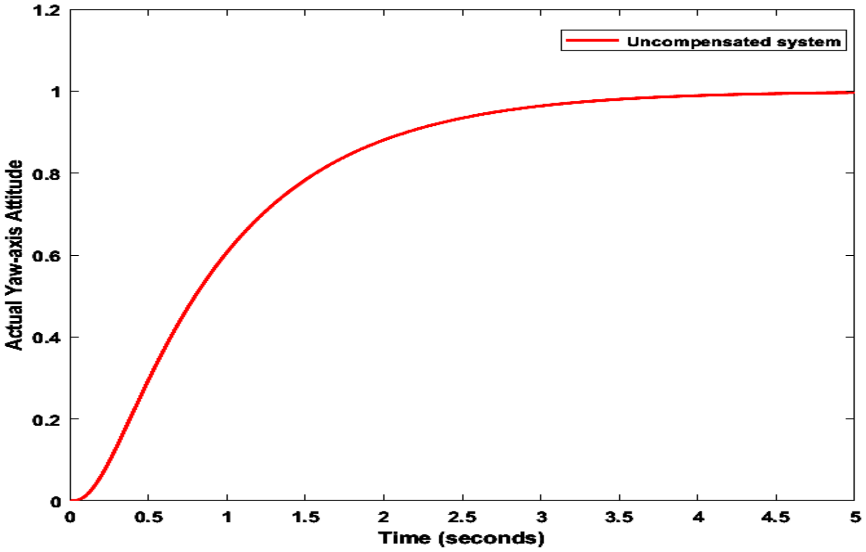

Figure 4: System response without controller

Table 1: Characteristics of uncompensated system

Parameter	**Value**
Rise time	1.89 s
Transient time	3.49 s
Settling time	3.49 s
Peak overshoot	0
Peak time	5
Final value	1
Steady state error	0

As shown in Table 1, without a controller, the system's transient and steady-state were characterized by rise time of 1.89 s, transient time and settling time 3.49 s respectively, peak overshoot of 0, peak time of 5 s, final value of 1 degree, and steady state error of 0. Figure 4 revealed that without 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). Therefore, it is necessary to design a controller for on-orbit flight performance improvement in terms of yaw angle.

3.2 Analysis of System with APD Controller

This subsection presents the simulation scenario regarding the step response of the system when the APD controller was introduced as a subsystem into the ACS. The simulation plot is shown in Figure 5 and the numerical analysis is shown in Table 2.

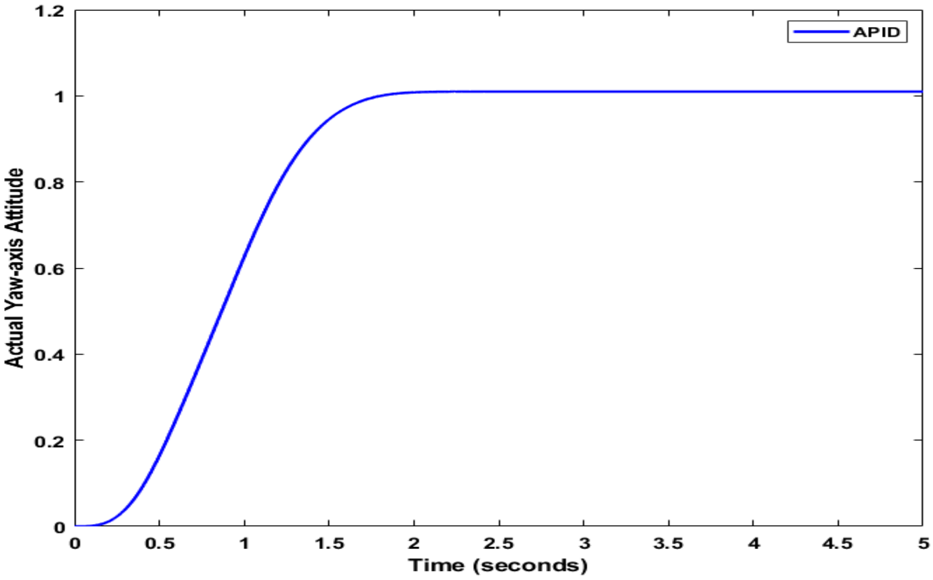

Figure 5: System's response with APD controller

Table 2: Characteristics of APD control system

Parameter	Value
Rise time	0.99 s
Transient time	1.71 s
Settling time	1.71 s
Peak overshoot	0
Peak time	5
Final value	1
Steady state error	0

It is evident from Figure 5 that the response of the APD control system time was faster than that of uncompensated system with rise time of 0.99 s as shown in Table 2. Also, the APD control system meets the performance criteria required of the system (looking at Table 2). Figure 6 shows the response curves and magnitude of K_p and K_d parameters of the designed APD.

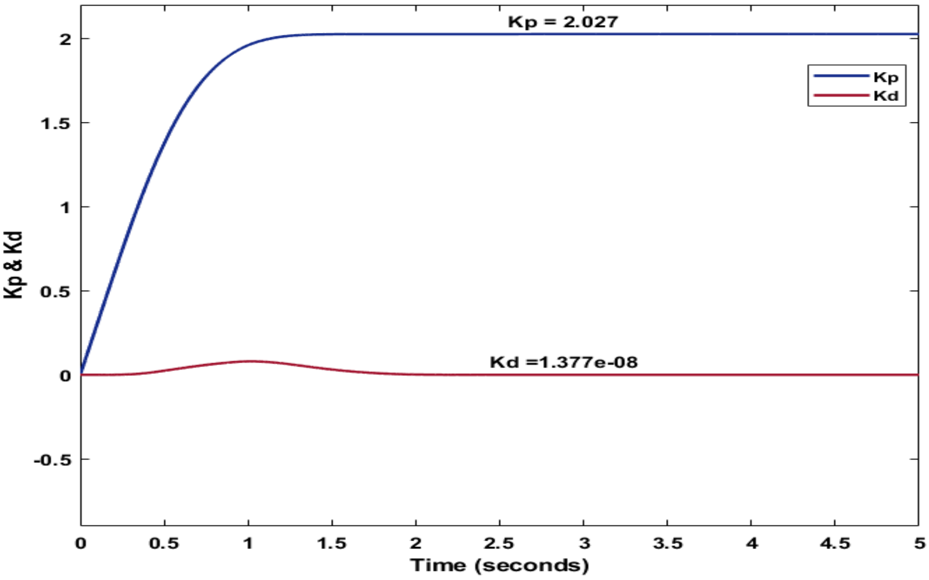

Figure 6: K_p and K_d plots

It is clear from theK_p and $K_d$plots shown in that at time t = 0, the APD parameters rise linearly and maintains steady values of 2.07 and 1.377e-08 when a steady-state is reached by the system corresponding to a settling time of 1.71 s as with the response in Figure 5. Further analysis was conducted regarding the performance of the amplifier and actuator to validate the APD effectiveness as shown in Figure 7.

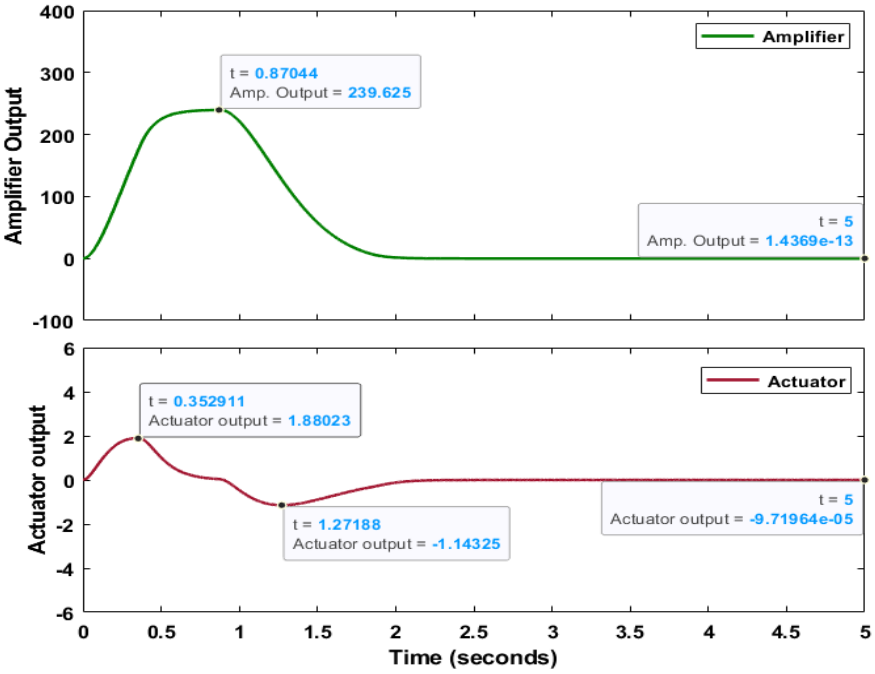

Figure 7: Amplifier and actuator plots

As shown in Figure 7 that the control signal from the controller is amplified to peak value of 239.6 and this corresponds to amplifier gain in Equation (1). As the system gradually approaches its steady and stable state, the dynamic response of the amplifier for the APD satellite yaw-axis ACS settles and goes to zero at 5 s when the control process is terminated. This is because as the desired yaw-axis attitude is approached, the error signal reduces to zero and simultaneously resulting in no control action and as such the amplifier output becomes zero. This is further revealed by the dynamic response of the actuator as shown in Figure 7.

3.2 Performance Comparison of Controllers

In order to ascertain the effectiveness of the designed APD controller is compared with previously applied control techniques by Ajiboye et al. (2020)on the considered microsatellite yaw axis ACS in this work. The simulation curves of the various control systems and the numerical analysis of the plots are shown in Figure 8 and Table 3The previous control systems were PID controller, PID with pre-filter (PIDF), PD, and PD with pre-filter (PDF).

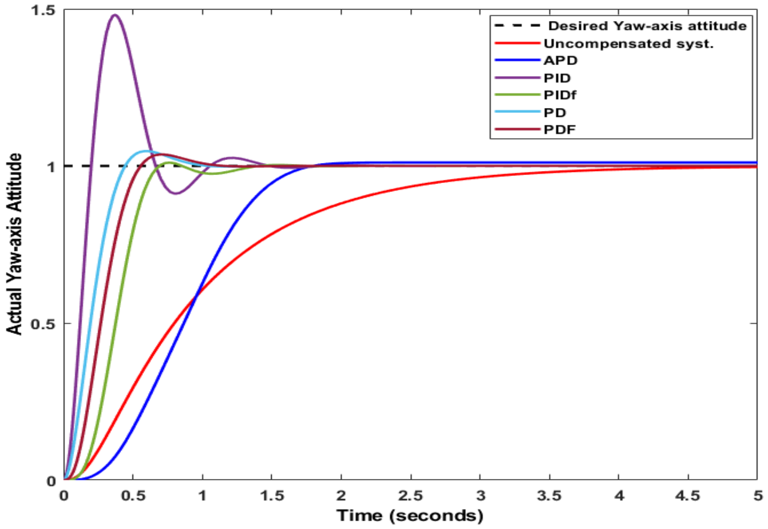

Figure 8: Response comparison for different control systems

Table 3: Yaw-axis attitude performance comparison of different control techniques

System condition	Rise time (s)	Transient time (s)	Settling time (s)	Peak overshoot (%)	Peak time (s)	Final value	e_{ss}
Uncompensated system	1.89	3.49	3.49	0	5	1	0
APD	0.99	1.71	1.71	0	5	1	0
PID	0.14	1.30	1.30	47.8	0.37	1	0
PIDF	0.37	1.17	1.17	0.92	0.76	1	0
PD	0.29	0.82	0.82	4.67	0.59	1	0
PDF	0.33	0.67	0.67	3.59	0.71	1	0

From Figure 8 and Table 3, it can be observed that the expected performance criteria were not met by the uncompensated system and the PID controller specifically the settling time and peak overshoot, respectively. The uncompensated system failed to provide the desired settling time required and instead offered a value of 3.49 s, while the PID offered 47.8% peak overshoot instead of a value less than or equal to 5% expected. The other controllers on the other hand, achieved the required design performance specifications. However, the designed APD controller provided the smoothest response and as such offered the finest control process stability for the microsatellite yaw-axis ACS.

IV. CONCLUSION

This paper has presented design of Adaptive PD (APD) controller for microsatellite yaw-axis attitude control system (ACS). In order to realize the objective of this paper, the dynamic equations representing the behaviour of a microsatellite yaw-axis in attitude control system were established. The dynamic equations were then modelled using Simulink embedded blocks in MATLAB together with the APD. Each of the model components shows different features of Simulink. Simulations were conducted to evaluate the performance of microsatellite yaw-axis ACS for different control scenarios. The analysis revealed that the system performance varied with respect to controller integrated within the loop. Initial simulation without a controller indicated that the desired design criteria were not met and as such different controllers were introduced. PID controller yielded high overshoot response, which does not meet performance expectation required for efficient on-orbit satellite operation of yaw-axis attitude. With other control strategies, the system achieved all the necessary performance criteria. Generally, the designed APD offered the smoothest and stable control process for the microsatellite yaw-axis attitude dynamic.

REFERENCES

[1]. Eze, P. C., Jonathan, A. E., Agwah, B. C., and Okoronkwo, E. A. (2020). Improving the performance response of mobile satellite dish antenna network within Nigeria.*Journal of Electrical Engineering, Electronics, Control and Computer Science, 6*(21), 25-30.

[2]. Eze, P. C., Ekengwu, B. O., Asiegbu, N. C., and Ozue, T. I. (2021).Adjustable gain enhanced fuzzy logic controller for optimal wheel slip ratio tracking in hard braking control system. *Advances in Electrical and Electronic Engineering,* 19(3),231 – 242.http://dx.doi.org/10.15598/aeee.v19i3.4124

[3]. Achebe, P. N. and Muoghalu, C. N. (2024). State-space modelling and control of two-phase hybid stepping motor for robot grinding using LQR controller. *International Journal of Academic Information Systems Research,8*(4), 132-136.

[4]. Achebe, P. N. (2018). Design of digital cascade compensator for ground station satellite antenna servo control system. *International Journal of Latest Engineering Science, 1*(3), 26-31.

[5]. Onyeka, E. B., Chidiebere, M., & Achebe, P. N. (2018). Performance improvement of antenna positioning control system using model predictive controller. *EuropeanJournal of Advances in Engineering and Technology, 5*(9), 722-729.

[6]. Ekengwu, B. O., Eze, P. C., Muoghalu, C. N., Asiegbu, C. N., and Achebe, P. N. (2024). Design of Robust Centralized PID Optimized LQR Controller for Temperature Control in Single-Stage Refrigeration System. *Indonesian Journal of Electrical Engineering and Informatics, 12*(3), 726-738. DOI: 10.52549/ijeei.v12i3.5629

[7]. Eze, P. C. Njoku, D. O., Nwokonkwo, O. C., Onukwugha, C. G., Odii, J. N., and Jibiri, J. E. (2024). Wheel Slip Equilibrium Point Model Reference Adaptive Control Based PID Controller for Antilock Braking System: A New Approach. *International Journal of Automotive and Mechanical Engineering, 21*(3), 11581 – 11595. https://doi.org/10.15282/ijame.21.3.2024.10.0893

[8]. Eze, P. C., Obichere, J. K., Mbonu, E. S., and Onojo, O. J. (2024). Positioning Control of Satellite Antenna for High Speed Response Performance. *IPTEK, The Journal of Engineering, 10*(2), 119-136. http://dx.doi.org/10.12962/j23378557.v10i2.a20670.

[9]. Ajiboye, A. T., Popoola, J. O., Oniyide, O., &Ayinla, S. L. (2020).PID controller for microsatellite yaw-axis attitude control system using ITAE method.*TELKOMNIKA Telecommunication, Computing, Electronics and Control, 18*(2), 1001-1011. DOI: 10.12928/TELKOMNIKA.v18i2.14303

[10]. Shan, Y., Xia, L., & Li, S. (2022). Design and simulation of satellite attitude control algorithm based on PID. *Journal of Physics: Conference Series, 2355* 012035. DOI:10.1088/1742-6596/2355/1/012035

[11]. Bello, A., Olfe, K. S., Rodríguez, J. Ezquerro, J. M., &Lapuerta, V. (2023).Experimental verification and comparison of fuzzy and PID controllers for attitude control of nanosatellites.*Advances in Space Research, 71*, 3613-3630. https://doi.org/10.1016/j.asr.2022.05.055

[12]. Narkiewicz, J., Sochacki, M., &Zakrzewski, B. (2020). Generic model of a satellite attitude control system. *International Journal of Aerospace Engineering, Volume 2020,* Article ID 5352019, 1-17. https://doi.org/10.1155/2020/5352019

[13]. Enejor, E.U., Dahunsi, F. M., Akingbade, K. F., & Nelson, I. O. (2023). Low Earth orbit satellite attitude stabilization using linear quadratic regulator. European Journal of Electrical Engineering and Computer Science, 7(3), 17-29. http://dx.doi.org/10.24018/ejece.2023.7.3.505

[14]. Eze, P. C., and Ezenugu, I. A. (2024). Microsatellite yaw-axis attitude control system using model reference adaptive control based PID controller. *International Journal of Electrical Computer Engineering Research, 4*, 8-16. https://doi.org/10.53375/ijecer.2024.389