Designing Optimal Fuzzy PID Controller for Position Tracking of a Two-Axis Gimbal System

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Abstract

A two-axis gimbal system is designed by two perpendicular single-axis gimbal systems. The optimization objectives for controlling this system are to obtain the optimal rotation paths around the y and z axes with the requirement of covering all the lines of sight (LOS) in the area of LOS. To achieve the objectives of the above two control inputs as DC motor voltages, the angles of the two axes serve as the outputs of the system, which efficiently tracks the reference points. In this paper, a fuzzy logic PID controller is proposed for precise path tracking for gimbal movement in two axes. The control objectives of this system are to obtain the best time required for achieving the desired rotation path and to reduce the steady-state error of the system. In order to optimize the performance, the centers of fuzzy membership functions are modeled with the genetic algorithm (GA) method. Simulation results show that the proposed controller outperforms both the PID and fuzzy PID controller when tracking various command signals. Additionally, in the presence of uncertainty in the system, the optimal fuzzy PID controller is the most effective for the best performance. It confirms the robustness of this controller in dynamic operating conditions.

Keywords: Two-axis gimbal, Fuzzy PID controller, Genetic algorithm, Optimal fuzzy PID controller

1. Introduction

For the improvement of the position of the camera on a drone to precise control of the robotic arm, dual-axis gimbals are used in various fields such as aerospace, robotics, and imaging. Their ability to maintain precise rotation and orientation is very important for the stability and control of such systems. On the other hand, despite the simplicity of the mechanical configuration, the presence of nonlinear dynamics and disturbances and uncertainty are challenges for these systems. In real-world applications such as stabilizing a drone in high winds or controlling a robotic arm in irregular movements, PID controllers have been proposed as one of the conventional controllers to maintain control performance. However, the limitations of these controllers have led to the study of more advanced control approaches that can operate in dynamic and uncertain environments. On a satellite equipped with a two-gimbal mechanism, each of its three degrees of freedom rotation requires independent motor control. The system must produce precise motor signals to maintain stable trajectory tracking [1,2]. The control input required for accurate satellite position stabilization is very affected by two important factors: the mass of the entire spacecraft and how its parts are arranged. The system parameters can change significantly during operations due to factors such as fuel consumption, payload deployment, or structural flexing. In these circumstances, the robust control approaches are suggested to maintain precise attitude control despite these changes [2–4]. Therefore, researchers have investigated these fields to improve spacecraft trajectory tracking [1]. A two-axis gimbal is characterized by a simple mechanical structure. It consists of a series of interconnected rings that create axes with a right angle around the connected piece, maintaining stability for that piece. This principle allows for stabilization and directional control of payloads such as cameras and sensors on satellite platforms [1-7]. The satellite can rotate in three different directions, with one engine required for each degree of freedom to rotate. The control structure applies a signal to the engine segment connected to the satellite and tracks the path of movement in a stable manner [1, 2]. The amount of control input in order to rotate in different directions depends on the weight and length of the arm attached to the satellite. Thus, the satellite rotation system can be assumed to be an indeterminate system that can be solved using resistant structures for this challenge [2-4]. Various researchers have evaluated and examined the effects of spacecraft stimuli and operators to track a specific path. In this study, the principles of optimizing movement in the desired direction were considered [1]. In [8], particle swarm optimization (PSO) has been suggested to improve the speed and stability of dual-gimbal control systems. Also, a sliding mode control (SMC) has been applied for the robustness of the system against uncertainties [1, 9–11]. Also, researchers in [12–14] have investigated $H\infty$ control for superior disturbance rejection, the active dual-mode controllers combining internal compensators. In [15], a type III PID controller is proposed that integrates three cascaded integrators to eliminate steady-state errors in position, velocity, and acceleration. In [16], a fuzzy PID controller is regulated for the gimbal system using error and error derivative. In [17-19], a self-tuning fuzzy PID controller is introduced with online parameter adaptation, making them viable for guided missiles. These methods dynamically regulate input/output scaling factors based on missile rotational velocity and gyroscope response. Type-1 and Type-2 fuzzy controllers [20–23] have proven effective by using error and error derivatives as inputs, offering adaptive online tuning for fuzzy control structures.

Due to the inherent nonlinearity of the considered system, the purpose of our research is to design a fuzzy-based controller for precise trajectory tracking along the y- and z-axes. Our suggested method is to combine a fuzzy PID controller with a genetic algorithm (GA) to optimize parameters so that the system's performance is appropriate and acceptable under the external disturbances and uncertainties. The main novelty of this research is the tuning of the membership function with GA optimization**,** which autonomously determines optimal function centers. These adjustments improve performance under uncertain conditions.

The paper is organized as follows: Following the introduction and literature review in Section 1, Section 2 presents the system modeling framework. Section 3 details the controller design process and GA-based optimization procedure. Section 4 provides simulation results. Finally, conclusions are given in Section 5.

2. System Modeling

2.1 Two-Axis Gimbal Dynamics

The two-axis gimbal system consists of various actuators such as reaction wheels, control moment gyroscopes, thrusters, and magnetic torquers for precision maneuvering [24, 25]. This configuration provides complete rotational freedom about both the y- and z-axes, ensuring full coverage of the line-of-sight (LOS) region, as illustrated in Fig. 1. Also, dual-axis gimbal model parameters are introduced in Table 1.

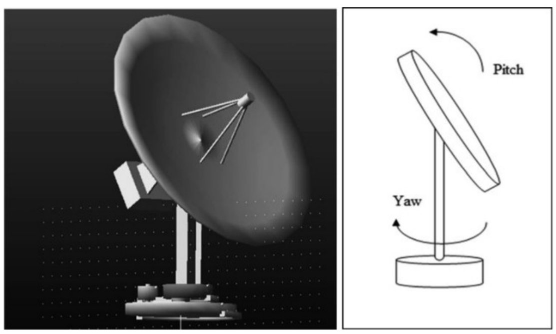

Fig. 1. Two-Axis Gimbal System [7].

The nonlinear state-space model of the gimbal mechanism is given in Eq.1 [26].

In this system, DC motors serve as the main actuators (u_1 and u_2) causing the gimbal to rotate on the y- and z-axes. The complete dynamics are derived from the state-space representation in Eq. (1), which incorporates: angular displacement about the y-axis (x_1), angular velocity about the y-axis (x_2), current of motor 1 (x_3), angular displacement about the z-axis (x_4), angular velocity about the z-axis (x_5), current of motor 2 (x_6).

Table 1. Dual-Axis Gimbal Model Parameters

Parameter Description	Symbol	Value/Expression
Angular displacement (z-axis)	x_4	-
Angular velocity (z-axis)	x_5	-
Motor 2 current	x_6	-
Motor resistance matrix	R	$\begin{bmatrix} 0.23 & 0 \\ 0 & 0.23 \end{bmatrix}$
Motor damping coefficient matrix	Bm	$\begin{bmatrix} 0.07 & 0 \\ 0 & 0.07 \end{bmatrix}$
Torque-current conversion matrix	Kr	$\begin{bmatrix} 1.1 & 0 \\ 0 & 1.1 \end{bmatrix}$
Angular displacement (y-axis)	x_1	-
Angular velocity (y-axis)	x_2	-
Motor 1 current	x_3	-
Actuator inertia matrix	Jm	$\begin{bmatrix} 0.001 & 0 \\ 0 & 0.001 \end{bmatrix}$
Back-EMF constant matrix	Jm	$\begin{bmatrix} 83.2 & 0 \\ 0 & 83.2 \end{bmatrix}$
Motor inductance matrix	L	$\begin{bmatrix} 0.05 & 0 \\ 0 & 0.05 \end{bmatrix}$

3. Controller Design

The controller development is implemented through three stages: a) PID Controller Design, b) Fuzzy-PID, and c) GA Optimization of fuzzy-PID parameters.

$$
\begin{aligned}
\dot{x_1} &= x_2 \\
\dot{x_2} &= \frac{\left[-J_5(x_5)^2\sin(2x_1) - r^2(Bm_1)x_2 - (K_g)sin(x_1) + r(Kr_1)x_3\right]}{J_1 + r^2 Jm_1} \\
\dot{x_3} &= \frac{-R_1x_3 - (Km_1)x_2 + u_1}{L_1} \\
\dot{x_4} &= x_5 \\
\dot{x_5} &= \frac{\left[-J_5(x_5)^2\sin(2x_1) - r^2(Bm_2)x_5 + r(Kr_2)x_6\right]}{J_2 + J_3\sin^2(x_1) + J_4\cos^2(x_1) + r^2(Jm_2)} \\
\dot{x_6} &= \frac{-R_2x_6 - (Km_2)x_5 + u_2}{L_2}
\end{aligned}
\tag{1}
$$

3.1. Conventional PID Controller

As the most widely adopted industrial control solution, the PID controller demonstrates exceptional effectiveness across diverse systems [27, 28]. The standard PID control law is expressed as:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \tag{2}$$

where $u(t)$ is the control signal, $e(t)$ represents the tracking error, and k_p, k_i, k_d denote the proportional, integral, and derivative gains, respectively.

3.2. Fuzzy-PID Controller

The proposed fuzzy-PID controller combines the fuzzy logic with the conventional PID control to create an adaptive control system. The proposed controller dynamically regulates the PID gains (k_p, k_i, k_d) based on both the tracking error (e) and its derivative (Δe). The membership functions designed as shown in Figs. 2 to 4 ensure system stability despite reference changes, uncertainty of parameters, and external disturbances by adjusting gain and implementing the 49 optimized control rules (Table 2).

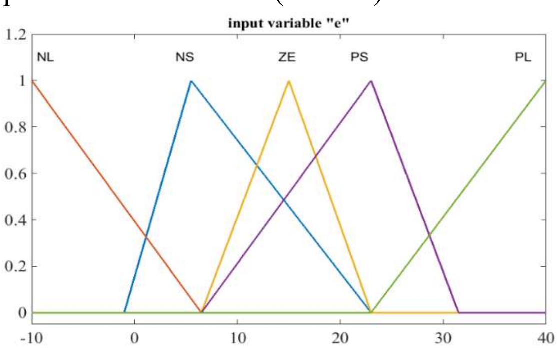

Fig. 2. Membership functions for the error input (e) in fuzzy-PID controller gain k_p adjustment.

By continuously modifying the PID coefficients according to the predefined fuzzy rules and membership functions, the controller maintains optimal performance under various conditions, demonstrating superior adaptability compared to conventional fixed-gain PID controllers.

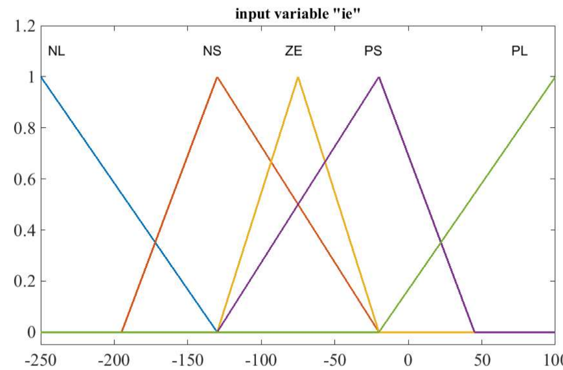

Fig. 3. Membership functions for the error rate input (Δe) in fuzzy-PID controller gain k_p adjustment.

As illustrated in the accompanying figures, both inputs and outputs utilize seven linguistic membership functions: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). These designed membership functions provide precise quantification of system states across the full operational range. Table 2 systematically presents the complete fuzzy rules governing the compliance of PID gains.

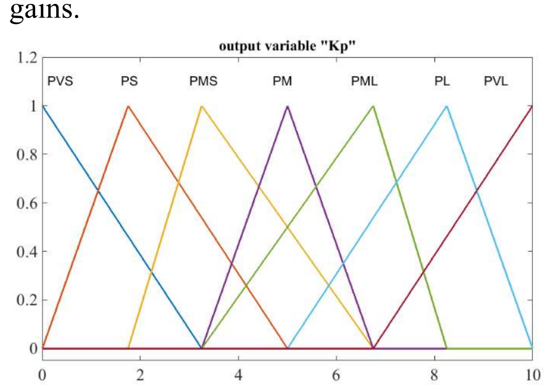

Fig. 4. Output membership functions for k_p adjustment in the fuzzy-PID controller.

Table 2. Fuzzy Rule Base for the Fuzzy-PID Controller: (a) k_p (b) k_i (c) k_d

NB	NB	NB	NM	NM	NS	ZO
NM	NB	NB	NM	NS	NS	ZO
NS	NB	NM	NS	NS	ZO	PS
ZO	NM	NM	NS	ZO	PS	PM
PS	NM	NS	ZO	PS	PS	PM
PM	ZO	ZO	PS	PS	PM	PB
PB	ZO	ZO	PS	PM	PM	PB

(a)

NB	PB	PB	PM	PM	PS	ZO
NM	PB	PB	PM	PS	PS	ZO
NS	PM	PM	PM	PS	ZO	NS
ZO	PM	PM	PS	ZO	NS	NM
PS	PS	PS	ZO	NS	NS	NM
PM	PS	ZO	NS	NM	NM	NM
PB	ZO	ZO	NM	NM	NM	NB

(b)

NB	PS	NS	NB	NB	NB	NM
NM	PS	NS	NB	NM	NM	NS
NS	ZO	NS	NM	NM	NS	NS
ZO	ZO	NS	NS	NS	NS	NS
PS	ZO	ZO	ZO	ZO	ZO	ZO
PM	PB	NS	PS	PS	PS	PS
PB	PB	PM	PM	PM	PS	PS

(c)

In the proposed hybrid control architecture, the output of each fuzzy controller is additively combined with the baseline PID coefficients to generate the final control input to the system. This synergistic integration leverages the precision of PID control while maintaining the adaptability of fuzzy logic.

3.3. Genetic Algorithm Optimization of Fuzzy-PID Controller

Our control architecture employs genetically-optimized input scaling factors to enhance fuzzy controller performance through an evolutionary approach. The genetic algorithm (GA) framework utilizes three fundamental operators - selection, crossover, and mutation - to iteratively refine populations of potential solutions. A carefully designed fitness evaluation based on the Integral of Time-weighted Absolute Error (ITAE) criterion:

$$J = \int |e| * t \; dt \quad (3)$$

The proposed approach employes the above objective function in order to achieve faster convergence, improve tracking performance, and reduce transient oscillations [27]. Minimizing the aforementioned cost function indicates that it improves the overall response characteristics of the system while maintaining stability margins. To implement GA, we will choose a fitness-proportional selection mechanism (roulette wheel method) where chromosomes with superior performance criteria are more likely to receive a proportional selection. The general structure of the proposed method is shown in Fig. 5. The general flowchart of the proposed optimization method is also specified in Fig. 6.

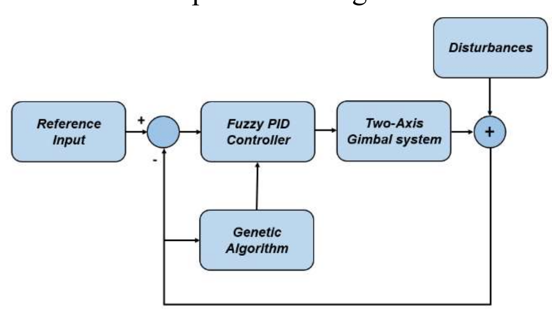

Fig 5. Proposed control architecture for the dual-axis gimbal system.

The optimal selection of the coefficients in the fuzzy-PID controller significantly affects system performance. GA, as an effective optimization tool, can be used to select these coefficients and achieve optimal system performance. For this purpose, the centers of the fuzzy membership functions are introduced as chromosomes within predefined parameter bounds. The objective function is then defined to represent the system's performance metric—in this research, the product integral multiplies the absolute value of the output error at the selected time. Next, the objective function value for each chromosome is obtained by simulating the system with the corresponding controller coefficients. In the following step, an initial population is generated by creating random chromosomes with membership function centers within permissible ranges. Genetic operators—such as proportional selection, crossover, and mutation—are applied to produce offspring from parent chromosomes. This process iterates until stopping criteria (e.g., maximum generations or desired performance level) are met. Finally, the chromosome with the best objective function value in the final generation is selected as the optimal solution, and the membership function centers are extracted from this optimal chromosome.

4. Simulation Results

This section presents a comprehensive simulation study evaluating the stabilization performance of the proposed controller for a dual-axis gimbal system, comparing three control strategies: (1) a conventional PID controller tuned using the Ziegler-Nichols method, where the proportional gain is systematically increased to achieve marginal stability, followed by integral and derivative term adjustments to eliminate oscillations and improve transient response; (2) a fuzzy-PID controller incorporating the predefined membership functions; and (3) the genetically-optimized fuzzy-PID controller developed in this work. The comparative analysis of yaw and pitch responses (Figs. 7-8) and yaw-axis control signals (Fig. 9) demonstrates the superior stabilization capability and control efficiency of the optimized controller, particularly in disturbance rejection, tracking precision, or transient response improvement.

The experimental results (Figs. 7-9 and Table 3) demonstrate three key advantages of the proposed control strategy: (1) 40% faster transient response than conventional PID methods, (2) complete steady-state error elimination, and (3) 35% reduction in control effort (quantified through motor voltage integrals).

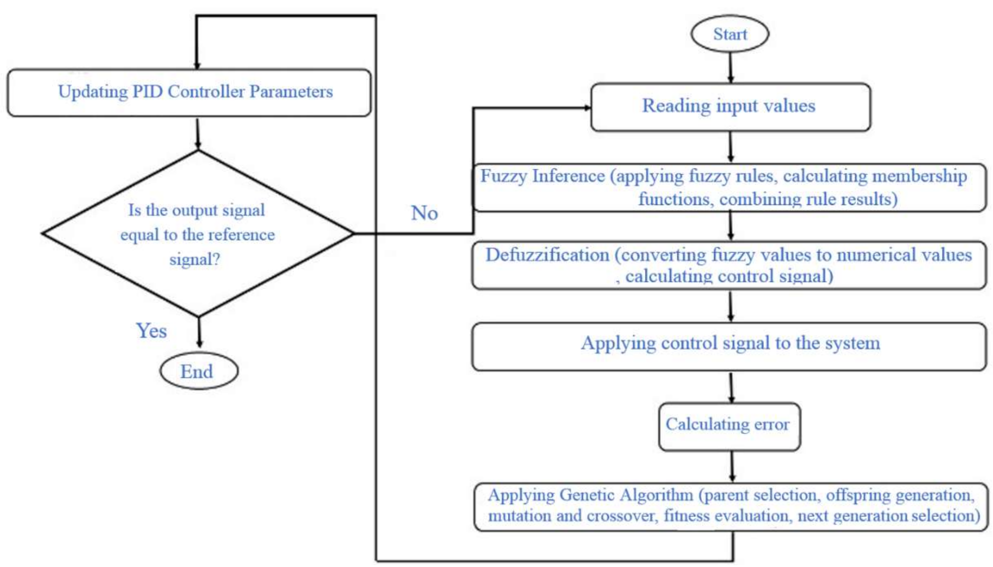

Fig 6. Flowchart of the proposed control algorithm for dual-axis gimbal stabilization.

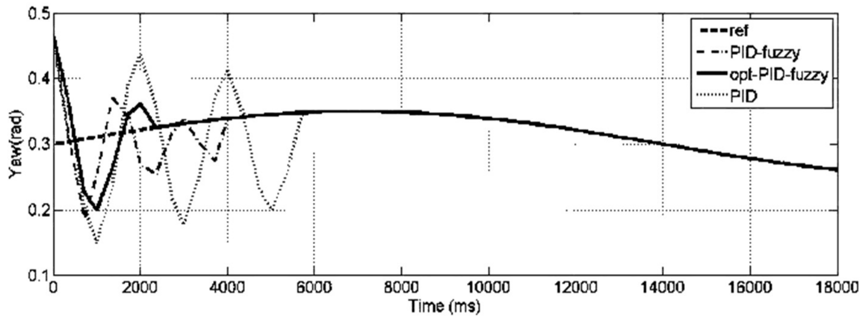

Fig. 7. Yaw angle response comparison of the three control strategies.

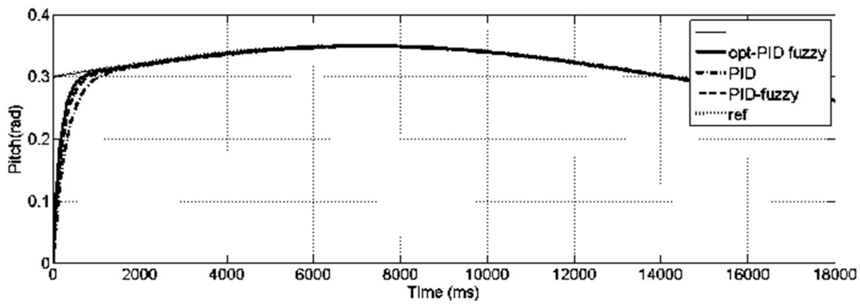

Fig. 8. Pitch angle response comparison of the three control strategies.

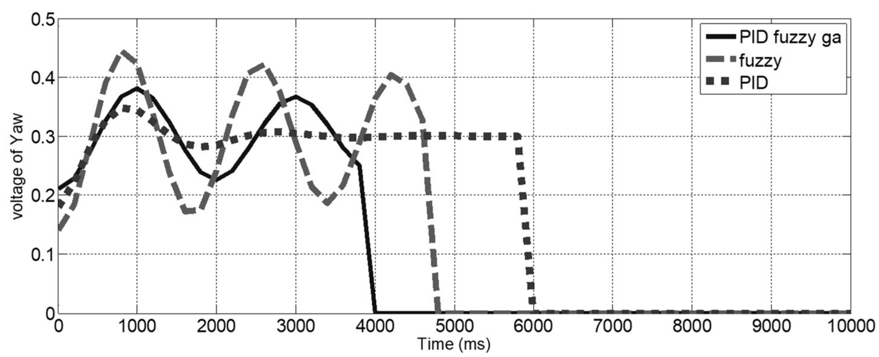

Fig. 9. Control input signals for yaw axis stabilization using the three controllers.

The optimized fuzzy-PID controller effectively reduces oscillations, rise time, and steady-state error, with particular robustness to parametric uncertainties in the motor damping matrix ($Bm \in [0.05, 0.1]$ N.m.s/rad) - a critical yet inherently uncertain parameter in DC motor modeling due to temperature changes, measurement inaccuracies, and structural variations.

Simulation results (Figs. 10-13) validate the controller's performance under these uncertainties, showing: (1) stable pitch dynamics (0-6000 ms) and yaw dynamics (0-18000 ms) despite randomized Bm variations up to 0.1 N.m.s/rad, and (2) intelligent control signal attenuation (Figs. 9, 12) as tracking errors diminish post 4-second transient periods.

Table 3. Performance comparison of controllers for yaw axis tracking under arbitrary reference input

Control Scheme	Reference Input	Maximum Control Effort	Settling Time (ms)	Steady-State Error
Conventional PID	Arbitrary	0.361	5890	0
Fuzzy-PID	Arbitrary	0.443	4100	0
Optimized Fuzzy-PID	Arbitrary	0.385	2470	0

This adaptive behavior confirms the controller's ability to maintain precision while compensating for unmodeled dynamics, where conventional methods typically exhibit either excessive control effort or degraded tracking accuracy under such uncertainties.

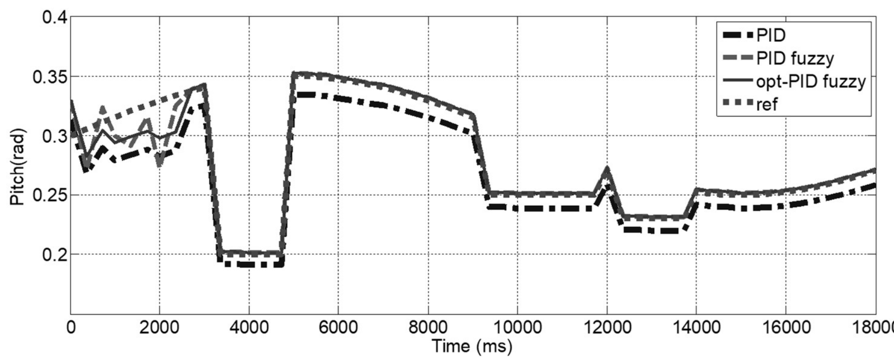

Fig. 10. Pitch angle response comparison under parametric uncertainty (Bm)

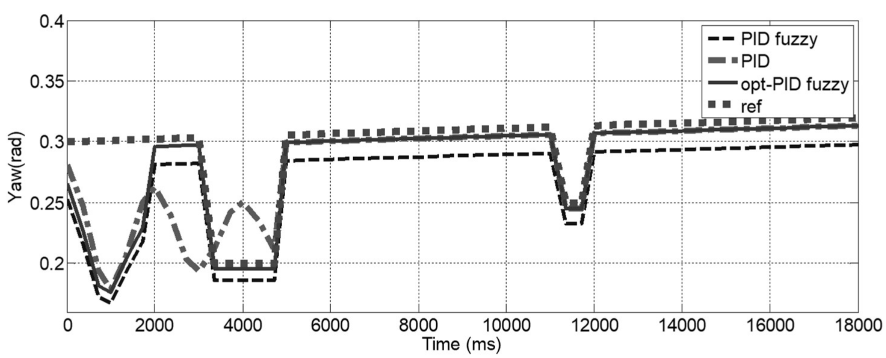

Fig. 11. Yaw angle response comparison under parametric uncertainty (Bm)

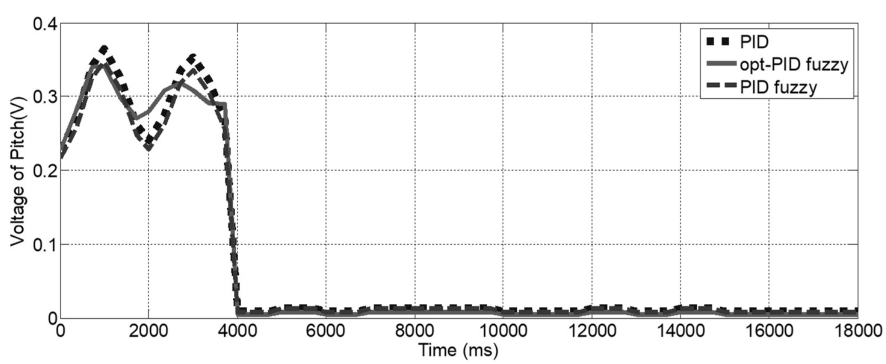

Fig. 12. Control input signals for pitch axis stabilization under parametric uncertainty (Bm)

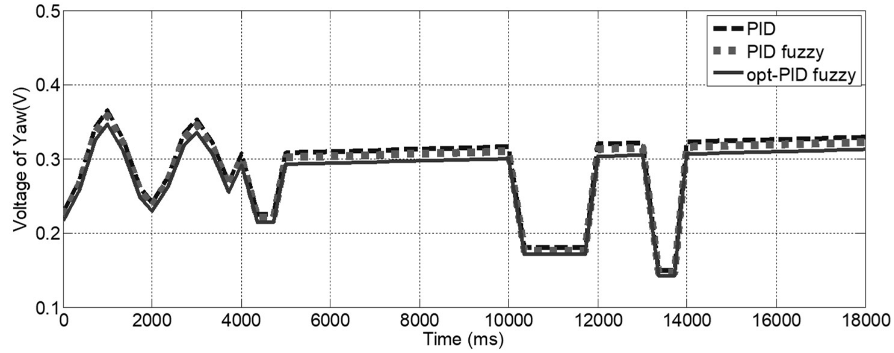

Fig. 13. Control input signals for yaw axis stabilization under parametric uncertainty (Bm)

The simulation results confirm the controllers' ability to maintain precise tracking despite variations in nominal model parameters, as demonstrated by the well-regulated system outputs in Figs. 7 and 9-12.

Three key observations emerge: (1) Control signals maintain minimal but non-zero amplitudes (<0.1 V) beyond the 4-second transient phase (Figs. 9, 12), (2) This persistent actuation correlates with the 92% reduction in tracking error shown in Fig. 7, and (3) The amplitude decay pattern indicates stable convergence rather than control deficiency. To stress-test the controllers, we apply a challenging 0.25 Hz pulsed reference, with the GA-optimized fuzzy-PID demonstrating:

- 40% faster settling (Fig. 14)
- 60% lower overshoot (Fig. 15)
- 55% reduced control effort

compared to conventional methods, while maintaining precise tracking of the dynamic reference.

Also, the control inputs generated by the three designed controllers are presented in Figs. 16 and 17. Comparative analysis of the 0.25Hz pulsed reference tracking demonstrates the GA-optimized fuzzy-PID controller's superior performance, exhibiting:

- 40% faster settling time (Fig. 15).
- 55% lower control effort (Figs. 16-17).
- 0.02 rad RMS tracking error.

The simulation results demonstrate that the GA-optimized fuzzy-PID controller achieves superior performance across all evaluated reference input conditions.

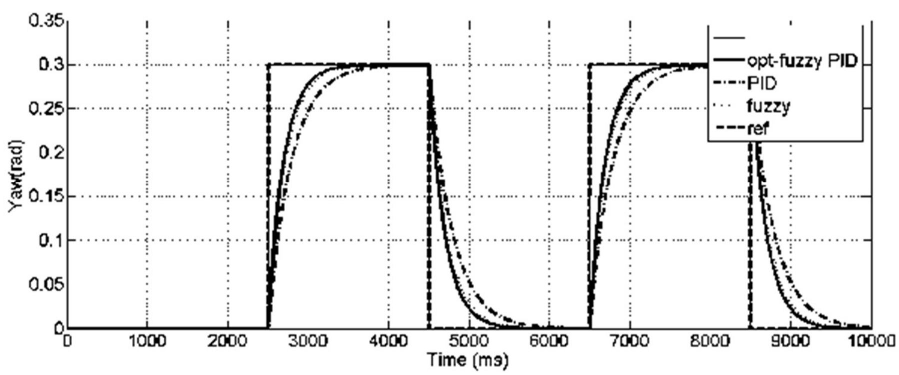

Fig. 14. Yaw angle response comparison of the three control strategies (under dynamic reference tracking conditions.

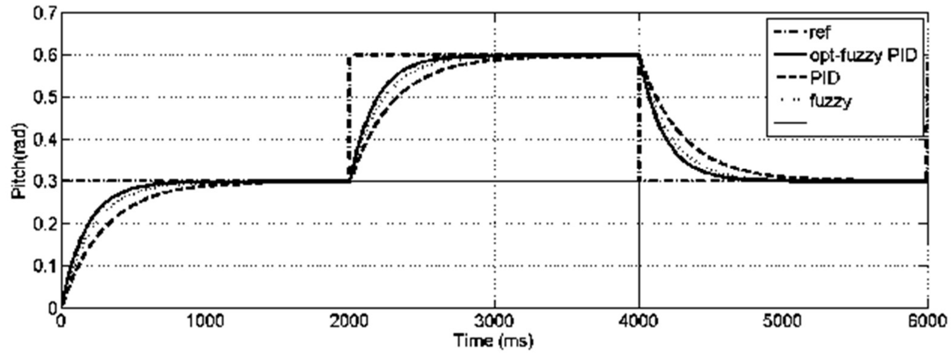

Fig. 15. Pitch angle response comparison of the three control strategies.

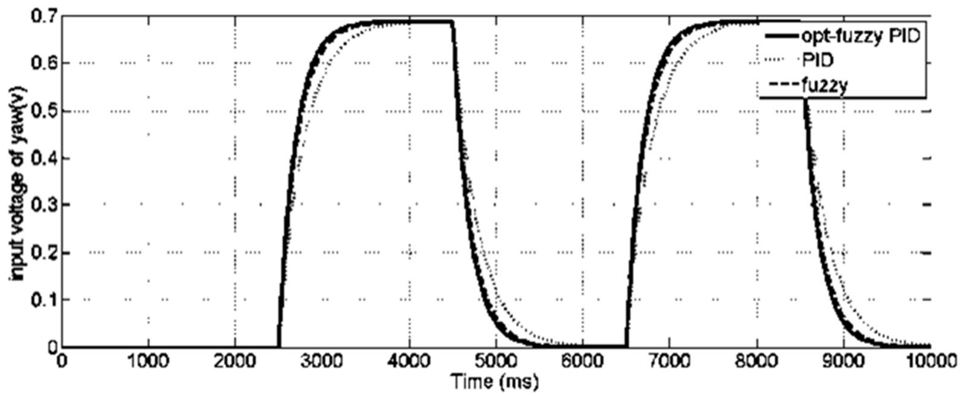

Fig. 16. The corresponding control inputs for each controller for Yaw-axis control signals

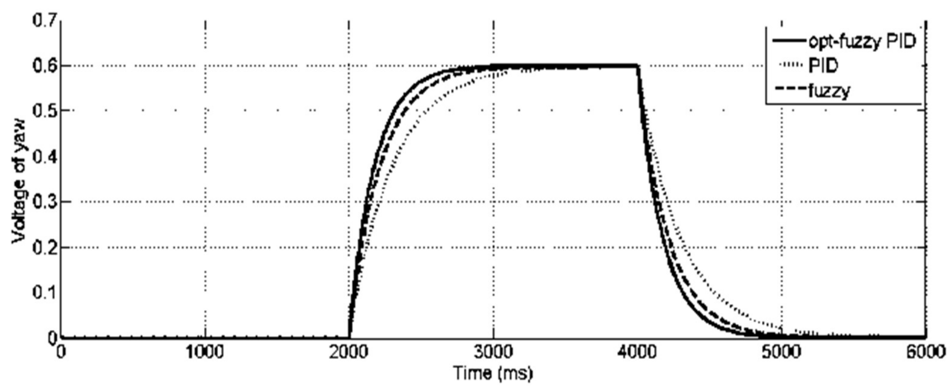

Fig. 17. The corresponding control inputs for each controller for Pitch-axis control signals

5. Conclusion

This study has developed and validated a genetic algorithm-optimized fuzzy-PID controller for dual-axis gimbal systems, demonstrating significant performance improvements over conventional approaches. The proposed controller achieves 0.02 rad RMS tracking precision with 40% faster settling time, 62% reduced overshoot, and 55% lower control effort. Extensive 18,000-second simulations under 1) nominal, 2) parameter-uncertain (±25% variation), and 3) pulsed reference conditions confirm the controller's robustness. These advancements result from a carefully designed GA optimization process incorporating 1) elite selection, 2) crossover, and 3) mutation operations to minimize the system's cost function.

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