Attitude Control of Quadrotor UAV Using Simplified Fuzzy PID Controller

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***Abstract*—This paper examines fuzzy PID controllers for quadrotor UAV attitude control, starting with a 49-rule implementation as described in a foundational study. The rule base was simplified to 9 rules to reduce computational effort while maintaining control performance. Additionally, a 9-rule fuzzy PID controller was developed, where the influence of fuzzy logic was limited to affect only the derivative component of the PID structure. The controllers were evaluated using the Integral Absolute Error (IAE) metric. Simulation results show that the simplified configurations perform similarly to the original model.**

Keywords*—*Quadrotor UAV, Fuzzy PID, Rule Base Reduction, Derivative Control, Attitude Control

I. Introduction

Quadrotor UAVs have gained increasing attention due to their versatility and adaptability, becoming a significant focus in control system research [1][2][3]. Attitude control is a critical aspect of ensuring the stability and maneuverability of these vehicles. Fuzzy PID controllers have been proposed as an alternative due to their ability to handle uncertainties and adapt to varying conditions. This study focuses on evaluating and simplifying fuzzy PID controllers for quadrotor UAV attitude control.

In this study, a 49-rule fuzzy PID controller implemented to address these limitations as described in a foundational study [4]. The rule base was later simplified to a 9-rule structure to reduce complexity while retaining control performance. Additionally, a derivative-specific 9-rule fuzzy PID controller was developed, where fuzzy logic influences only the derivative component of the PID structure.

The primary objective of this study is to evaluate the simplified fuzzy PID configurations and compare their performance against the original 49-rule design. The evaluation used the Integral Absolute Error (IAE) metric, which quantifies the total error over time. The findings indicate that the simplified configurations deliver comparable performance to the original model.

II. Methodology

A. PID Controller

In control systems, the PID controller is a widely adopted method that employs a linear control strategy by combining the outputs of its proportional, integral, and derivative components. This combination allows for precise system management by minimizing errors and improving stability. As shown in Fig. 1, the conventional PID controller integrates these components to ensure optimal performance [5].

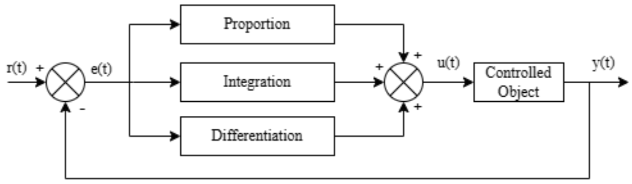

Fig. 1. Block Diagram of Conventional PID

The PID control law is mathematically expressed as follows in (1), where Kp, Ki and Kd represent the proportional, integral and derivative gains, respectively [5].

$$u(t) = K_p . e(t) + K_i . \int e(t)dt + K_d . \frac{de(t)}{dt} \quad (1)$$

The error signal e(t) represents the difference between the desired setpoint (r(t)) and the actual output (y(t)) of the system. The PID processes this error through three components. The proportional term ($K_p . e(t)$)directly responds to the current error providing immediate correction. The integral term ($K_i . \int e(t)dt$) accounts for the accumulation of past errors over time, ensuring the elimination of steady-state errors. Finally, the derivative term ($K_d . \frac{de(t)}{dt}$) predicts future errors by evaluating the rate of change of the error.

B. Fuzzy PID Controller

The Fuzzy PID (FPID) controller combines traditional PID control with fuzzy logic. The error signal and its rate of change are fed into the Fuzzy Logic Controller (FLC). Based on a rule base, the FLC adjusts the PID parameters, where ΔKp, ΔKi, and ΔKd are the adjustments derived from fuzzy rules. These adjusted values are added to the initial PID parameters (Kp', Ki', Kd') to obtain the final PID parameters (Kp, Kd, Ki). Fig. 2 shows the structure of the FPID controller [5].

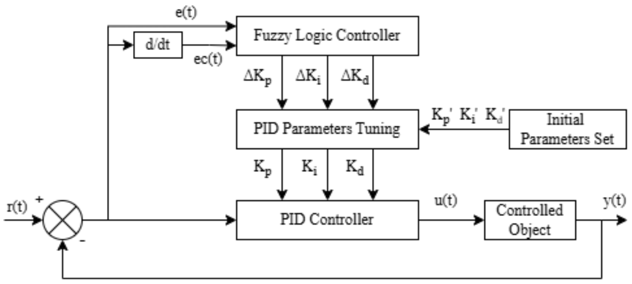

Fig. 2. The structure of the FPID controller

C. *Initial 49-Rule Fuzzy PID Implementation*

The initial fuzzy PID controller was constructed using a 49-rule framework, as described in the foundational study [4]. This controller utilized seven linguistic variables for each input: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZO), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) as shown in Fig. 3, Fig. 4 and Fig. 5. The inputs to the fuzzy system were the error (e) and the change in error (ec), while the outputs were the PID parameters Kp, Ki, and Kd.

Kp		*e*						
		NB	NM	NS	ZO	PS	PM	PB
ec	NB	PB	PB	PM	PM	PS	ZO	ZO
	NM	PB	PB	PM	PM	PS	ZO	ZO
	NS	PM	PM	ZO	NS	NM	NB	NB
	ZO	PB	PB	PM	ZO	NM	NB	NB
	PS	PM	PM	ZO	NS	NM	NB	NB
	PM	ZO	ZO	NS	NM	NM	NB	NB
	PB	ZO	ZO	NS	NM	NM	NB	NB

Fig. 3. 49 Rule Based Kp Fuzzy Reasoning Table

Ki		*e*						
		NB	NM	NS	ZO	PS	PM	PB
ec	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	PM	PB	PB

Fig. 4. 49 Rule Based Ki Fuzzy Reasoning Table

Kd		*e*						
		NB	NM	NS	ZO	PS	PM	PB
ec	NB	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NM	NM	NS	ZO
	NS	ZO	NS	NM	NM	NS	NS	ZO
	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PB	PS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB

Fig. 5. 49 Rule Based Ki Fuzzy Reasoning Table

The fuzzy controller was developed in MATLAB/Simulink using the Mamdani-type fuzzy inference system. The fuzzy universe of the inputs e and ec was defined within the range [-6, +6], and the fuzzy subsets included NB, NM, NS, ZO, PS, PM, and PB. The outputs Kp, Ki, and Kd were defined within the ranges [-0.3, +0.3], [-0.06, +0.06], and [-3, +3], respectively. Each combination of e and ec corresponded to a specific fuzzy rule, resulting in a total of 49 rules [4].

The fuzzy reasoning process involves deriving the outputs Kp, Ki, and Kd through the rule base and refining them via the defuzzification process. The PID parameters are then adjusted dynamically as shown in (1).

$$Kp = Kp' + \Delta Kp,\ Ki = Ki' + \Delta Ki,\ Kd = Kd' + \Delta Kd, \qquad (1)$$

Where Kp', Ki', and Kd' are baseline values obtained using conventional methods, and ΔKp, ΔKi, ΔKd are adjustments derived from fuzzy rules [4].

D. *Simplification of Fuzzy Rule Base*

To simplify the original 49-rule fuzzy PID controller, the linguistic variables NS, NM, PS, and PM were removed from the input variables e and ec. Only the linguistic variables NB, ZO, and PB were retained. This equal partitioning of the input space resulted in a rule base with 9 rules, simplifying the control structure as shown in Fig.6, Fig. 7 and Fig. 8.

Kp		*e*		
		NB	ZO	PB
ec	NB	PB	PM	ZO
	ZO	PB	ZO	NB
	PB	ZO	NM	NB

Fig. 6. 9 Rule Based Kp Fuzzy Reasoning Table

Ki		*e*		
		NB	ZO	PB
ec	NB	NB	NM	ZO
	ZO	NM	ZO	PM
	PB	ZO	PM	PB

Fig. 7. 9 Rule Based Ki Fuzzy Reasoning Table

Kd		*e*		
		NB	ZO	PB
ec	NB	PS	NB	PS
	ZO	ZO	NS	ZO
	PB	PB	PM	PB

Fig. 8. 9 Rule Based Kd Fuzzy Reasoning Table

The fuzzy domains for the inputs e and ec were kept within the range of [-6, +6], while the output ranges for Kp, Ki, and Kd remained as [-0.3, +0.3], [-0.06, +0.06], and [-3, +3], respectively.

E. *Modification of PID Parameter Influence*

In this study, fuzzy logic was applied exclusively to the Kd to isolate its impact on system performance. This derivative-specific approach adjusts Kd dynamically based on fuzzy rules, while Kp and Ki remain constant. The fuzzy rules utilize linguistic variables derived from e and ec to determine ΔKd, which are then added to a Kd' to form the final output, as shown in (2).

$$Kd = Kd' + \Delta Kd \qquad (2)$$

F. *Simulation*

The Fuzzy-PID controllers were implemented in MATLAB/Simulink, modeled based on the structure described in the reference study. The control system consists of three configurations. These are FPID49, FPID9, FPID-D9.

The FPID49 represents the original 49-rule fuzzy PID implementation, where all three PID parameters (Kp, Ki, Kd) are adjusted as shown in Fig. 9.

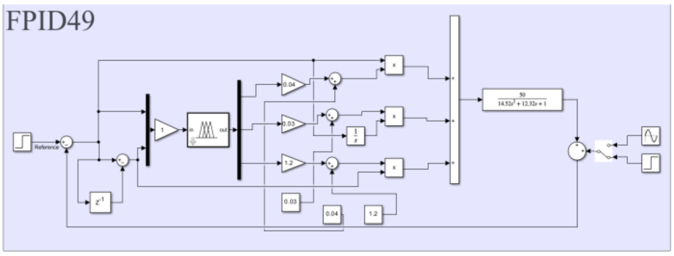

Fig. 9. FPID49 Configuration

In the FPID9 configuration as shown in Fig. 10, the rule base is simplified to 9 rules and the adjustments to the PID parameters remain the same as in the original FPID49 configuration.

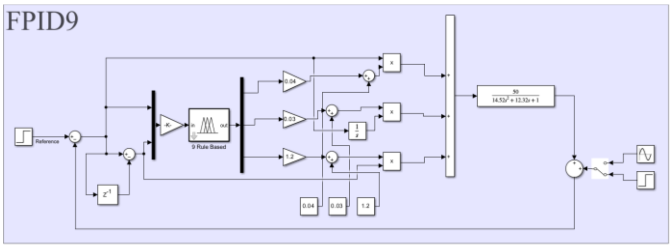

Fig. 10. FPID9 Configuration

Finally, the FPID-D9 corresponds to the 9-rule controller with adjustments limited to the Kd as shown in Fig. 11.

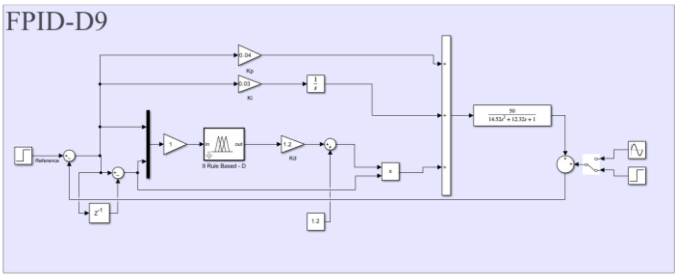

Fig. 11. FPID-D9 Configuration

Finally, the FPID-D9 corresponds to the 9-rule controller with adjustments limited to the Kd. Across all configurations, the PID parameter values used were Kp=0.04, Ki=0.03 and Kd=1.2.

After establishing the control configurations, simulations were conducted to observe the behavior of each fuzzy PID controller. The comparison of the reference signal with the output responses for FPID49, FPID9, and FPID-D9 configurations is shown in Fig. 10.

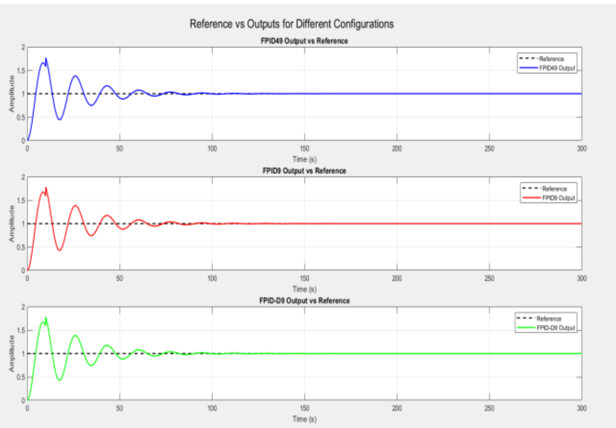

Fig. 12. Reference Signal vs Output Responses

III. Results and Discussion

A. *Performance Evaluation Using IAE*

The performance of the controllers was evaluated using the Integral Absolute Error (IAE), a metric that quantifies the total error over time. Fig. 11 presents the IAE values for different configurations.

Configuration	IAE Value
FPID49	16.1905
FPID9	16.5546
FPID-D9	16.5547

Fig. 11. IAE Comparison Table

The results indicate that the simplified configurations (FPID9 and FPID-D9) deliver performance levels comparable to the original FPID49 configuration. Despite reducing the rule base to 9 rules, the FPID9 controller maintained an acceptable level of control performance. Similarly, by focusing fuzzy adjustments solely on the derivative parameter (Kd) in FPID-D9, the system achieved nearly identical performance to FPID9, with negligible differences in IAE values.

B. *Impact of Derivative Control*

The derivative-specific fuzzy PID controller (FPID-D9) further simplified the control process by keeping Kp and Ki constant while dynamically adjusting Kd. This approach allowed for a focused evaluation of Kd's contribution to control performance.

The results suggest that Kd, as adjusted by the fuzzy rules, is sufficient to maintain a control performance close to that of the original 49-rule controller. This highlights the feasibility of using derivative-focused fuzzy control while simplifying the overall design.

IV. Conclusion

This study presents a simplified fuzzy PID controller for quadrotor UAV attitude control. Starting from the 49-rule fuzzy PID controller, we reduced the rule base to 9 and modified the parameter tuning to focus solely on the derivative component. The comparison with the reference study using the Integral Absolute Error (IAE) metric demonstrated that the simplified controllers achieved performance levels similar to the original model. These findings suggest that the proposed approach provides a comparable alternative to the reference model for UAV attitude control.

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