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Flight Controller Design for Altitude Control of a Quadcopter using PID and Fuzzy Methods

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Abstrak

Sebuah quadcopter dapat dikendalikan secara manual atau dapat otonom. Oleh karena itu diperlukan suatu sistem kontrol untuk mendukung pergerakan quadcopter tersebut. Kendali PID dan fuzzy digunakan dalam penelitian ini untuk mengatur posisi ketinggian quadcopter. Sistem kendali yang diusulkan dalam penelitian ini adalah menjaga quadcopter pada ketinggian tertentu. Perancangan sistem kendali menggunakan pengendali PID, dimana parameter kendali diperoleh dengan menggunakan metode tuning Ziegler-Nichols 2. Metode tuning Ziegler-Nichols 2 digunakan untuk mendapatkan parameter Kp, Ti, dan Td. Tuning kendali PID menjadi acuan desain kontrol fuzzy dalam menentukan fungsi keanggotaan input dan output serta aturan-aturannya. Juga, dalam penelitian ini, desain papan pengendali penerbangan diusulkan. Hasil percobaan menunjukkan bahwa kendali PID memiliki rise time yang lebih cepat yaitu 0,2 detik, maximum overshoot yang lebih baik sebesar 1,56%, settling time yang lebih cepat yaitu 1,69 detik, dan error steady state sebesar 0% dibandingkan dengan kendali fuzzy. Hasil penelitian menunjukkan bahwa penggunaan kendali PID lebih cocok untuk pembangkit quadcopter yang diusulkan karena memerlukan respon output yang cepat.

Kata kunci: *quadcopter, kendali terbang, logika fuzzy, penyetelan PID, kendali ketinggian*

Abstract

A quadcopter can be manually controlled or can be autonomous. Therefore, a control system is needed to support the quadcopter's movement. PID and fuzzy control are used in this research to adjust the quadcopter's altitude position. The control system proposed in this research is to keep the quadcopter at a certain altitude. The control system design uses a PID controller, where the control parameters are obtained using the Ziegler-Nichols 2 tuning method. Ziegler-Nichols 2 tuning method is used to obtain the parameters K_p, T_i, and T_d. PID control tuning becomes a reference for fuzzy control design in determining input and output membership functions and the rules. Also, in this study, the flight controller board design is proposed. The experiment results show that the PID control has a faster rise time of 0.2 seconds, a better maximum overshoot of 1.56%, a quicker settling time of 1.69 seconds, and a steady-state error of 0% compared to the fuzzy control. The result shows that the use of PID control is more suitable for proposed quadcopter plants because it requires a fast output response.

Keywords: quadcopter, flight control, fuzzy logic, PID tuning, altitude control

I. INTRODUCTION

The quadcopter is an unmanned aerial vehicle (UAV) that can be used for various functions such as surveillance, search, rescue, or even entertainment. Quadcopters are nonlinear and underactuated, making them very attractive to control system researchers. As a result, the popularity of the technology applied to quadcopters is increasing in terms of design, technological features, and the type of flight control.

The quadcopter has four motors and propellers, enabling the quadcopter to be able to vertical takeoff and landing (VTOL), move in all directions, and can hover in the air. Many studies have been carried out to overcome control problems on quadcopters; some have synthesized control systems and validated them only through

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simulation, and some have validated on a real quadcopter (implementation). Research in [1] analyzes the performance of the quadcopter when path planning uses PID control. This research implements PID control and validates the proposed control through simulation only. In [2], who designed conventional PID and fuzzy controllers, where the proof of the proposed control was only to simulation. Research in [3] developed a Fuzzy PID controller to minimize problems related to slow response and poor robustness at a quadcopter altitude. The simulation results show that Fuzzy PID is effective in overcoming robustness.

In research [4]-[6], the researchers designed quadcopter controllers for various control problems, using PID control and fuzzy control. The research results are shown both in simulation and implementation. Finally, in research [7] designed, a PID controller aims to overcome the problem of quadcopter stability. The proposed method is tested based on experiments, and stability analysis is carried out using a statistical approach, namely Analysis of Variance (ANOVA).

On the other hand, the flight controller board design for quadcopters is a separate issue among researchers on how to design a flight controller board that fits the required specifications. Research [8] made a custom flight controller for the quadcopter; besides that, the quadcopter frame design was created so that it could be folded. This research shows a unique quadcopter design but only applies PID control in validating the proposed controller. Whereas [9], [10] made a cheap construction of a quadcopter using an Arduino controller board as the flight control. However, this researcher only proposed PID control as a quadcopter control method.

Based on the above problems, this research aims to develop a flight controller board based on a microcontroller, PID, and Fuzzy control design to overcome the quadcopter altitude position. The flight controller board design and PID and fuzzy control algorithms that can be implemented in embedded systems contribute to this research. Furthermore, the PID control parameter tuning approach minimizes mathematical computations in formulating quadcopter plant models. The tuning method used is Ziegler-Nichols type 2.

This paper is organized as follows, part II is the design of the flight controller board, and part III consists of the design of the PID control algorithm and the design of the fuzzy control. The result and discussion are in part III. Part IV is the result and discussion, while the conclusion is in part V.

II. RESEARCH METHOD

A. Quadcopter Design

Quadcopter has four motors and propellers at each tip of the main frame facing in the same direction. In this research, the quadcopter has a body frame with a cross structure. This cross structure is quite thin and light but demonstrates robustness by connecting the mechanical motor (which is heavier than the structure). Each propeller is connected to the motor via a reduction gear. All the axes of the propeller rotation are fixed, and parallel, and the airflow from the propeller is directed downwards (to obtain upward lift). The quadcopter design is assumed to have a rigid structure.

For the quadcopter to perform VTOL motion, vertical thrust is required. This thrust is generated from the same torque value of the four motors. Figure 1 illustrates the front, rear, right, and left motors that must have the same torque to fly. Then the front and rear motors have a counter-clockwise rotation, while the right and left motors have a clockwise rotation. Figure 2 shows the design of the quadcopter frame made. The body frame will have dimensions (L×W×H) of 450×450×220 millimeters.

B. Hardware Selection

The controller board design consists of a microcontroller, a Bluetooth module, and a LIDAR sensor (Figure 3). The microcontroller serves as a system processor, with the task of receiving the

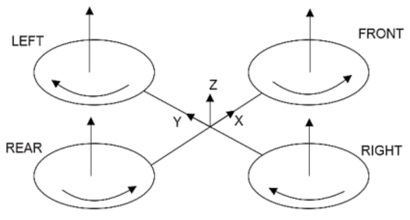

Figure 1. Illustration of motor motion on a quadcopter

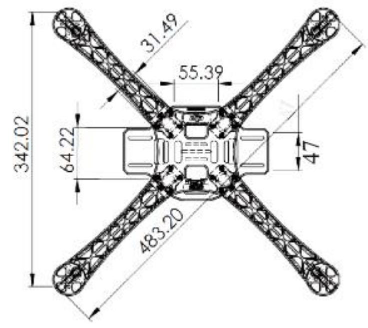

Figure 2. Frame of quadcopter

quadcopter altitude reading value (from the LIDAR sensor) and executing the control algorithm embedded in it. The control algorithm embedded in the microcontroller will adjust the speed of the manipulated value (MV) signal and send it to each BLDC motor through the electronic speed controller (ESC). The Bluetooth module is an interface between a microcontroller board and a personal computer to reading serial monitors and wirelessly upload programs.

This research focuses on quadcopter altitude control (position on the Z-axis). It only controls the VTOL movement with several assumptions: the angle position is considered balanced, and there is no control position requirement on the X and Y axes. Thus, the LIDAR sensor is used as a position sensor of altitude on the proposed flight controller board.

C. PID Control Design

The PID control system consists of P (proportional), I (integral), and D (derivative) controls. Each parameter will adjust the system output signal according to the desired system input and the configuration depicted in Figure 4. The mathematical Equation of PID control can be seen in (1).

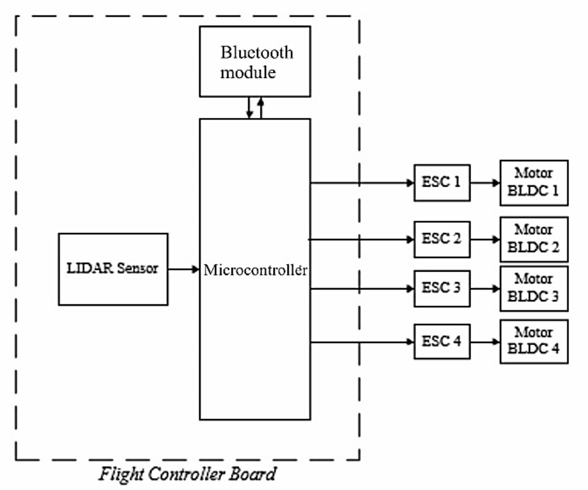

Figure 3. Hardware architecture

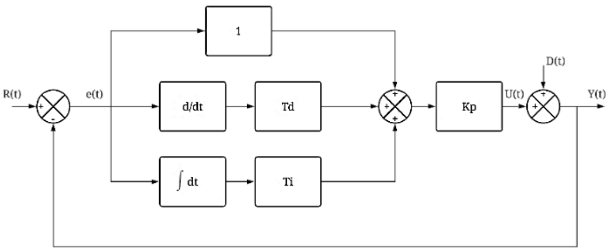

Figure 4. Configuration of PID controller

$$U(t) = K_p e(t) + K_p T_d \frac{de(t)}{dt} + \frac{K_P}{T_i} \int_0^t e(t)dt \tag{1}$$

where *U(t)* is the control action, *e*(*t*) is the error value resulting from the difference between the given set point and the output signal feedback, T_i is the time integral, and T_d is the time derivative. While K_p is the proportional gain, K_i is the integral gain, and K_d is the differential gain.

In this research, the initial parameters of Kp, Kd, and Ki were obtained using the Zieglers-Nichols type 2 tuning method. Based on the [11] study, the Ziegler-Nichols tuning method is carried out on an open-loop system by providing input whose magnitude increases gradually until the output response reaches sustained oscillation. Based on this method, the quadcopter's initial response is shown in Figure 5.

In Figure 5, values of K_{cr} (critical gain) with a value of 2 generate the results of the analysis of the P_{cr} value (critical period) with a value of 1.07 seconds. Furthermore, these two parameters K_{cr} and P_{cr} are substituted in Table 1 (Ziegler-Nichols rule type 2).

Based on Table 1, the values of Kcr and Pcr will be calculated to obtain the parameters of Kp, Ti, and Td. The calculation results get the value as depicted in (2).

$$K_p = 1{,}2;\ \ T_i = 0{,}535;\ \ T_d = 0{,}2675 \tag{2}$$

then, to determine the PID control algorithm for embedded systems by using discrete PID [11]. The PID control algorithm for embedded systems can be seen in Figure 6, where some of the equations in the image refer to [11].

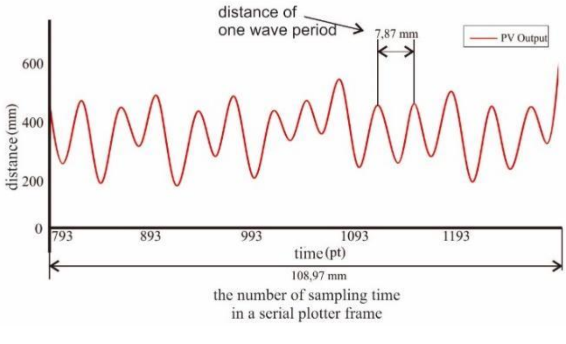

Figure 5. Sustain oscillation response

Table 1. Ziegler-Nichols type 2 tuning rules

Controller types	K_P	T_I	T_D
P	$0{,}5K_{cr}$	∞	0
PI	$0{,}45K_{cr}$	$\frac{1}{1{,}2}P_{cr}$	0
PID	$0{,}6K_{cr}$	$0{,}5P_{cr}$	$0{,}25P_{cr}$

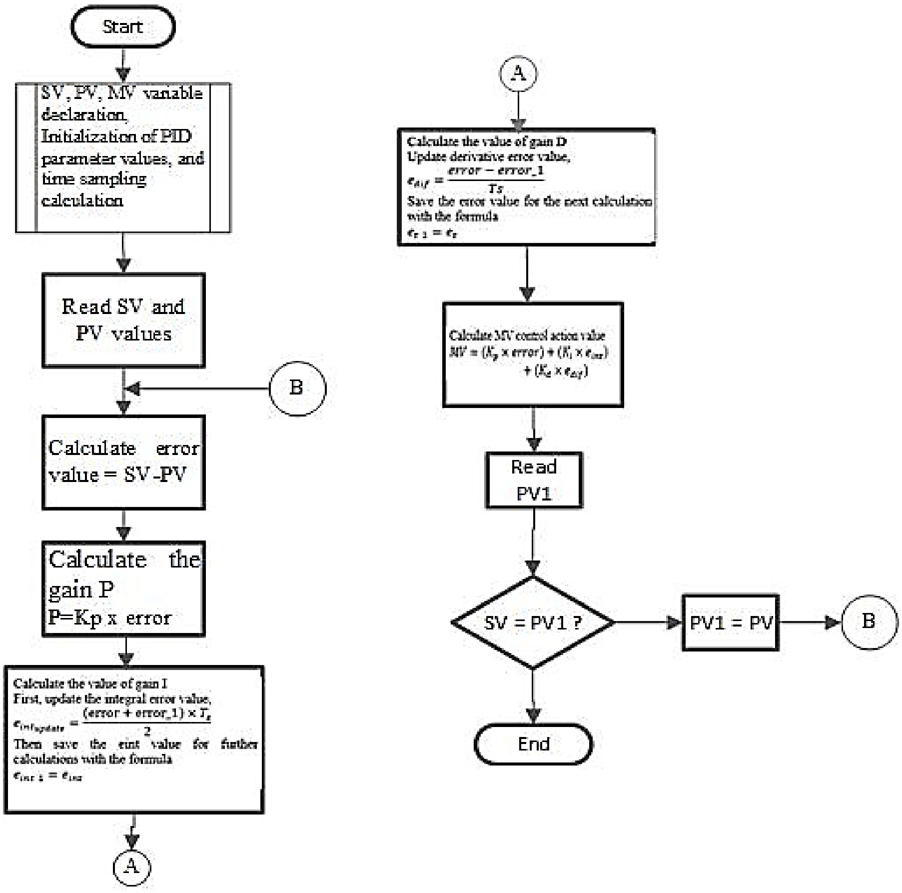

Figure 6. Discrete PID control algorithm

The integral error value is denoted by e_{int}, the microcontroller sampling time for each cycle is denoted by T_s, and e_{df} is the derivative error value. While SV is the set point value, PV is the process variable and MV is the manipulated value. The error value in this control algorithm is the quadcopter's altitude position error.

D. *Fuzzy Control Design*

In quadcopter altitude control, the object that can be controlled is the rotational speed of the BLDC motor. This Fuzzy control design has one input variable, namely altitude error, and one PWM output variable. The initial tuning of the PID control parameters becomes the reference for the fuzzy control design in determining the input and output membership functions and the rules made.

The membership function value from the input is divided into five membership functions (as shown in Figure 7), namely Negative Big (NB), Negative Small (NS), Medium (M), Positive Big (PB), and Positive Small (PS). Meanwhile, the membership function for output is divided into five membership functions, namely Very Slow (VS), Slow (S), Zero (Z), Fast (F), and Very Fast (VF) depicted in Figure 8. In this control design, the inference mechanism is 'max', and the defuzzification is 'centroid.' The rules made to determine the rules of PWM value at the output for a certain input error are as follows:

1. If (error is NB) then (PWM is VF) (1)
2. If (error is Medium) then (PWM is Z) (1)
3. If (error is PB) then (PWM is VS) (1)
4. If (error is NS) then (PWM is F) (1)
5. If (error is PS) then (PWM is S) (1)

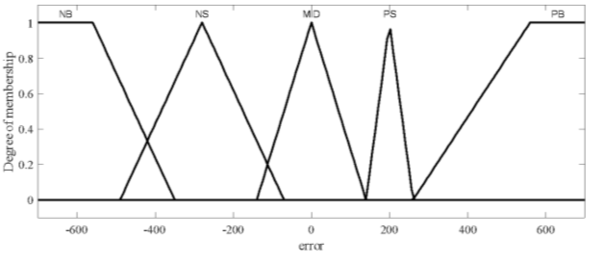

Figure 7. Membership function input error

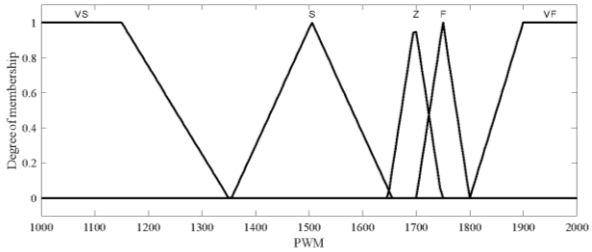

Figure 8. Membership function output PWM

III. RESULT AND DISCUSSION

Figure 9 shows the flight controller board that has been made, where (a) top view and (b) bottom view. The microcontroller used is an Arduino board, and the Bluetooth module used is the GFSK type with a frequency band of 2.4 GHz ISM. While Figure 10 is a whole body of a quadcopter (including a flight control board mounted on it). Figure 11 depicts the quadcopter's environment, with (a) the quadcopter ready to take off and (b) it has reached a height of 30 cm. Figure 12 depicts the external force that was applied.

Experimental tests are carried out by considering the preparation of the experimental environment. As it is known that a quadcopter can fly and hover at a certain height if all four motors have the same motor speed and achieving this condition requires a fully powered quadcopter. Furthermore, PID and fuzzy control can only work on systems that are active with maximum quadcopter power with propellers attached to them. Therefore, it was decided to make a test stand (Figure 11) for the quadcopter so that the testing procedure could be carried out more safely.

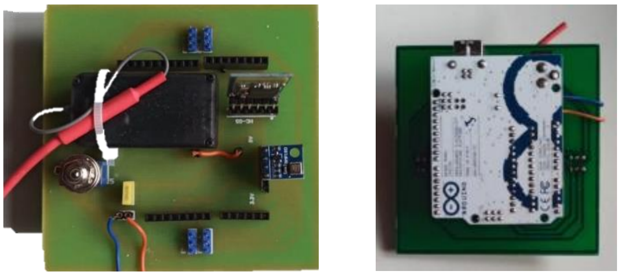
(a) (b)

Figure 9. Flight controller board that has been designed (a) top view, (b) bottom view

Figure 10. Proposed quadcopter

A. PID Control Test Verification

1) PID Control Response using Initial Parameter

The parameters K_p, T_i, and T_d, which have been calculated in (2), are then implemented in the quadcopter, and the quadcopter response can be seen in Figure 13.

Experiments were carried out by giving the desired distance of 500 mm, having a rise time of 6.6 seconds, settling time of 21.78 seconds, overshoot of 16%, and no steady-state error. However, because it still has an overshoot of 16%, the PID controller parameter tuning is carried out around the initial parameter values.

2) PID Control Tuning Result Response

In this research, the desired system specifications are zero error steady-state, maximum Overshoot of 5%, rise time, and settling time < 5 seconds.

The quadcopter did not obtain the desired specifications. So, the parameters control was tuned around the parameter values in (2). After tuning the control parameters several times, the best tuning results are found in (3).

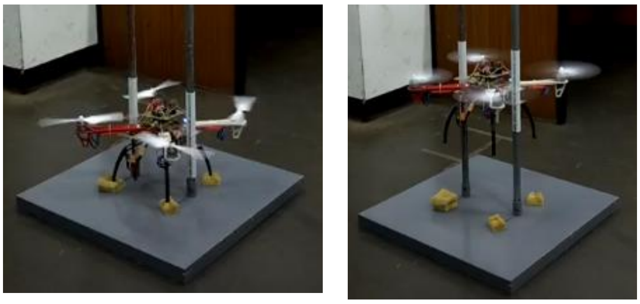
(a) (b)

Figure 11. (a) ready to take off, (b) reach 30cm of height

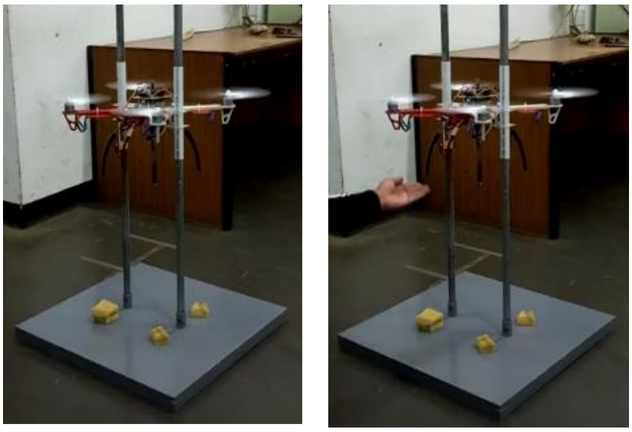
(a) (b)

Figure 12. (a) hover without disturbance, (b) external disturbance was applied

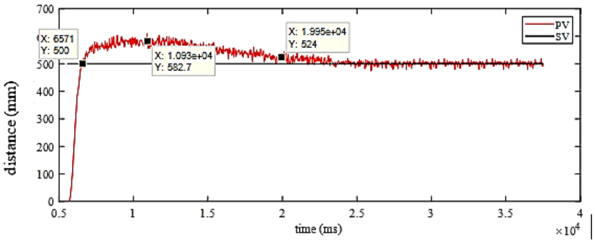

Figure 13. PID control initial response

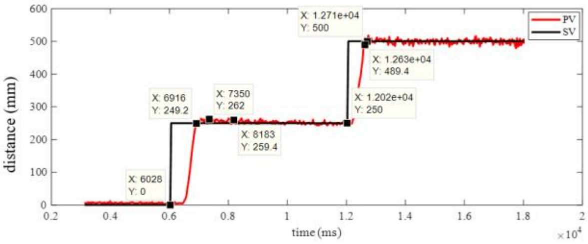

Figure 14. PID control tuning response

$$K_p = 1{,}2;\ T_i = 20;\ T_d = 0{,}1 \qquad (3)$$

The quadcopter response in Figure 14 shows a rise time value of 0.89 seconds, settling time of 2.2 seconds, overshoot of 1.6%, and no steady-state error. Meanwhile, for a distance of 250 – 500 mm, it has a rise time of 0.68 seconds, a settling time of 0.6 seconds, overshoot of 0%, and no steady-state error. Thus, the response has met the desired design specifications.

There are differences in the parameter values Between the initial PID parameters contained in (2) and the parameters of the tuning result in (3). The new tuning parameters in (3) aim to reduce the Overshoot and steady-state error values. In this research, the value of the integral gain (Ki) and the derivative gain (Kd) must be reduced to decrease the steady-state error and the Overshoot. Initial gain K_i and K_d are 2.2 and 0.321, respectively; the best tuning results are K_i and K_d 0.06 and 0.12, respectively.

3) *Disturbance Test on PID Control*

The disturbance test process is carried out by applying an external force to the quadcopter position, and then the response is observed after being disturbed.

The results of the disturbance test using the PID control algorithm (Figure 15) on the quadcopter plant show that the response after being disturbed can return to the desired set point.

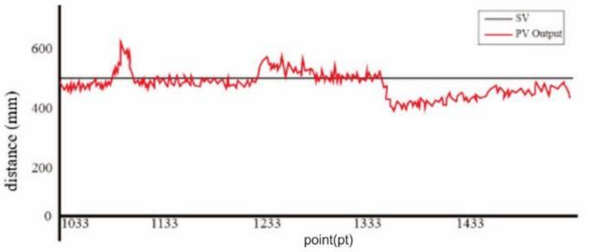

Figure 15. PID control disturbance test response

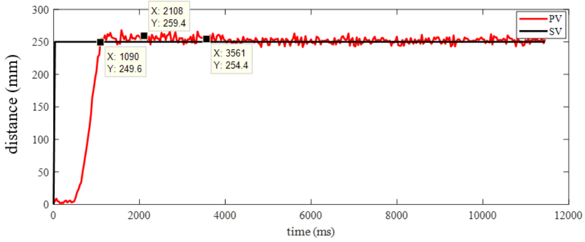

Figure 16. Fuzzy control response for a distance of 0 – 250 mm

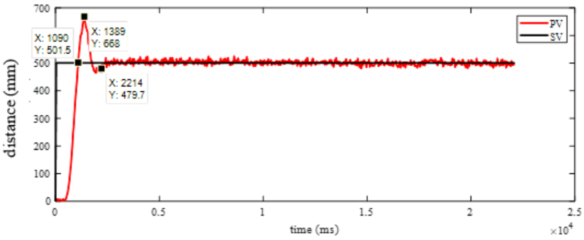

Figure 17. Fuzzy control response for distance 0 – 500 mm.

B. *Fuzzy Control Experiment Results*

Making fuzzy control was done intuitively, where observations were conducted during the experiment using PID control. All data obtained when testing the performance of the PID controller is used as a reference for making fuzzy control by explaining the dynamic behavior of the quadcopter and then transforming it into the proposed fuzzy control rules.

The fuzzy controller performance test results can be seen in Figure 16 and Figure 17. Figure 16 shows the response when given the desired height of 250 mm, while Figure 17 shows when given the desired position of 500 mm.

For a position of 0-250 mm, it has a rise time of 1.09 seconds, a settling time of 3.89 seconds, overshoot of 3.16%, and no steady-state error. Meanwhile, for a distance of 0-500 mm, it has a rise time of 1.08 seconds, a settling time of 2.2 seconds, an overshoot of 33.6%, and no steady-state error.

1) *Disturbance Test*

The disturbance test process is carried out by applying an external force to the quadcopter position, and then the response is observed. The

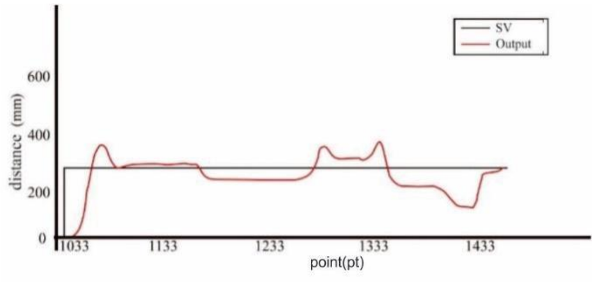

Figure 18. Fuzzy control disturbance test response

results of the disturbance test using the fuzzy control algorithm on the quadcopter plant show that the response after being disturbed does not return to the specified set point (as can be seen in Figure 18). This is because the membership function is designed as a PWM output that remains at a fuzzy value with a specific range. Unlike the PID control, when the response does not reach the set point, the integral gain will compensate for the error until the resulting control action can overcome the steady-state error. In principle, the integral gain will continue to add up the error value with the previous value. Thus, the fuzzy control applied to the quadcopter is not able to suppress steady-state errors as well as PID. This can be due to the rules or membership functions that are not too suitable to overcome the problems of quadcopter dynamics and nonlinearity. The disadvantage of fuzzy control is that it takes longer to observe plant dynamics and formulate appropriate rules.

IV. CONCLUSION

Based on the results of the design and testing that have been done, it can be concluded that the Flight Controller Board has been made and work well. The PID and Fuzzy controller designs have been successfully implemented on the flight control board. The response of the quadcopter plant from the PID tuning results for the 0-500 mm distance test has a rise time of 0.68 seconds, a settling time of 0.6 seconds, an overshoot of 0%, and no steady-state error. The response of the quadcopter plant when using Fuzzy control for testing distances of 0 -250 mm has a rise time of 1.09 seconds, a settling time of 3.89 seconds, an overshoot of 3.16%, and no steady-state error. When the quadcopter is given an external disturbance, the PID control shows a better performance in overcoming the disturbance than the fuzzy control. This is indicated because of the influence of the integral gain, which serves to overcome the steady-state error. The use of PID control is more suitable for quadcopter plants because it requires a fast output response.

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