T1-Fuzzy vs T2-Fuzzy Stabilize Quadrotor Hover with Payload Position Disturbance

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Abstract

In the previously work, T1-Fuzzy controller successful 75% of control Quadrotor 1-axis hover without a long oscillation while given an external disturbance in this case is payload positions. This T1-Fuzzy controller which designed before, only gives a good response which payload placed at the center and a half of arm Quadrotor. Without doing any change in Quadrotor components like controller board, four sets Electronic Speed Controller (ESC), four sets DC brushless motor, and also four sets propellers, T2-Fuzzy Controller performance tested and comparing to T1-Fuzzy Controller in previously work. In this paper also used a COG instrument like the previously work to validate a Center of Gravity (COG) of payload position variations. T2-Fuzzy which have a higher level to handle uncertainty and imprecision than T1-Fuzzy gave a better result about 100% begin a center position until payload position in ¾ arm Quadrotor.

Keywords: T2-Fuzzy, T1-Fuzzy, Quadrotor 1-axis, payload positions, COG instrument.

Introduction

In a last decade, research on Quadrotor growing fast. This Quadrotor as a flying robot can be categorized as a helicopter which has a VTOL (Vertical Take Off and Landing) systems have many advantages from other flying principles [1],[1]was compared with five flying principles; they are an airplane, helicopter, bird, autogiro, and blimp. Advantages and drawbacks of the Quadrotor were explained in[2].

The Quadrotor in cross configuration have four propellers. There is divided into two pairs of propellers. One pair moving in one direction with named propeller (1,3) and the other turn in opposite directions with named propeller (2,4). With making
speed variations through increasing and decreasing four propeller’s speed together, Quadrotor can lift force and set up a vertical motion. Four propellers Quadrotor conceptsis shown in Figure 1 [3].

Quadrotor have two model configurations[4]. Quadrotor + and X flight configurations. The difference between them is shown in Figure 2. Quadrotor + flight configuration pointing an arm in the navigation direction, in X flight configuration with the navigation direction in the middle plane between two arms[4]. Quadrotor mostly used Brushless Direct Current (BLDC) motor. This BLDC motor is a permanent magnet where the magnetic fields are uniformly spread in the air gap. The back EMF has a trapezoidal shape in time when the motor is turning at constant speed[5]. The important feature of the BLDC motor by detection rotor position. It is very possible to generate inverter control signals to control motor speed variations. The BLDC motor is shown in Figure 3.

An Electronic Speed Controller (ESC) can control BLDS motor if its input gave signal named speed control signal. The signal for speed control is called a Pulse Width Modulation (PWM) signal. It has a period around 20 ms and varies from 0.5 to 1.5 ms. This model controls signal like as servo signal. Electronic Speed Controller (ESC) model is shown in Figure 4. The primary operation of the main controller of Quadrotor such as a measurement, action loop, control realized by local micro-controller[3].

![Figure 1. Quadrotor Concept](image1)

![Figure 2. Quadrotor + and X Flight Configurations](image2)

![Figure 3. BLDC Motor](image3)

![Figure 4. Electronic Speed Controller (ESC)](image4)
In many articles explained that development control systems Quadrotor requires advance test bed or test bench[1, 2, 3]. This test bed or test bench intended for reducing control complexity and to avoid the Quadrotor broken easily. This paper presents a comparison between T1-Fuzzy and T2-Fuzzy Control testing analysis based on payload positions for improvement BLDC efficiency when Quadrotor take some payload.

This paper has four sections followed by a conclusion. The structure, hardware and software system of the Quadrotor frame design and electronics are described in Section 2. Section 3 describes the design T1-Fuzzy and T2-Fuzzy Controller. The Quadrotor 1-axis flight on the test bed with T1-Fuzzy as a control and T2-Fuzzy as a control described in section 4, indicates the oscillation for each payload positions and BLDC working efficiency analysis.

**Quadrotor Design**

**Quadrotor Frame**

In this paper, Balsa wood used as a material in this paper for built-in because in Indonesia this kind of materials can be found very easy. A Balsa Quadrotor showed in Figure 5. This Quadrotor uses the new model of Quadrotor called H-Quadrotor.

**Electronic Components of Quadrotor**

Almost all Quadrotor have a similar electronic components. Quadroon has 4 units Electronic Speed Controller, Turnigy Plush 30A, 4 units Brushless DC Motor 1275 KV, and 4 units triangle propellers. Arduino Mega be used for main control. Turnigy Li-Po battery 2200 mAH as a main energy supply.

In this research utilized MMA7361 as an accelerometer sensor, and GS-12 as a gyroscope sensor. All electronic components are shown in Figure 6. All data signal from that two sensors to main control (Microcontroller) and data signal from microcontroller to BLDC motor through ESC utilize servo signal with period 20 ms and varies from 0.9 to 1.9 ms pulse. Block diagram hardware connection is shown in Figure 7.

**Figure 5.** H-Quadrotor with Balsa Material

**Figure 6.** Electronic Components
Fuzzy Control Design

T1-Fuzzy Control

Quadrotor systems have complexity like as 6-dof robot [9]. It had higher uncertainty level. T1-Fuzzy Controller was a solution for many applications with uncertainty systems. Nevertheless, T1-Fuzzy Controller design is a not an easy task for fuzzy logic practitioner every time that they try to use T1-Fuzzy Controller as a solution to some problems[7]. The T1-Fuzzy Controller structure is shown in Figure 8.

A T1-Fuzzy Set, A notation is characterized by a Membership Function (MF) \( \mu_A(z) \) [7] where \( z \in Z \), and \( Z \) notation is the domain of definition of the variable, i.e.

\[
A=\{(z, \mu(z))| oz \in Z\}
\]

where \( \mu(z) \) is called a T1-Membership Function (MF) of the T1-Fuzzy Set A. Membership Function for each element of \( Z \) to a membership value between 0 and 1. T1-Fuzzy Inference Systems (FIS) is numerical systems that map crisp inputs into a crisp output. Every T1-FIS is associated with a set of rules with linguistic interpretations, such as:

\[
R^1: \text{IF } y \text{ is } A^1 \text{ AND } y' \text{ is } A^2 \text{ THEN } u \text{ is } B^1
\]

In this paper, to get the crisp output of Figure 8, we do computation a Centroid of Area (COA)[10] as T1-Fuzzy defuzzifier. The COA is defined by:

\[
Z_{COA} = \frac{\sum \mu(z)z}{\sum \mu(z)}
\]

where \( \mu(Z) \) is the output aggregate of the T1-Fuzzy. This is defuzzification strategy, which the calculation of expected values in probability distributions.

T2-Fuzzy Control

As the T1-Fuzzy set, the concept of T2-Fuzzy set as an extension of the concept of an ordinary fuzzy set was introduced by Zadeh. Fuzzy Logic Systems (FLS) contain at least one T2-Fuzzy set is called a T2-FLS. T1-FLS are unable to directly handle rule uncertainties and imprecision, because they use T1-Fuzzy sets that are
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certain. On the other side, T2-Fuzzy FLS, are very useful in circumstances where it is difficult to determine an exact, and measurement uncertainties and imprecision [10]. T2-Fuzzy FLS be very useful to be used when the circumstances are too uncertain to determine exact membership grades. A structure of a T2-Fuzzy FLS is shown in Figure 9.

![Figure 8. T1-Fuzzy Controller Structure](image1)

![Figure 9. T2-Fuzzy Controller Structure](image2)

T2-Fuzzy Algorithm in general form requires a long time because it is very complex mathematics calculations. Many researchers are knowing how to simplify the type-reduction. Fast geometric defuzzification method is fast type-reduction without loss the T2-Fuzzy uncertainties form [11]. In this method, the defuzzification process is not through the type-reduction stage as on T2-Fuzzy general, but fast geometric defuzzification approaches rely on geometric polyhedron [12,13]. In this paper realizes the T2-Fuzzy fast geometric defuzzification method in real-time. The model of Polyhedron illustrated in figure 10. T2-Fuzzy membership function set is divided into five areas. The five areas are the top surface (a), bottom surface (b), the rear surface (c), the front surface (d), the bottom surface (e).

The following sequence of steps Fast Geometric defuzzification using this method. And for realize in Microcontroller Arduino, needs array form to do it. (1) Do three points on the Geometric discretization of fuzzy set of crisp input as many as twelve points x. (2) Make forming geometric triangular matrix of five areas from areas (a), area (b), area (c), area (d), and area (e) according to the algorithm above. (3) After getting the point x, y, z of each discretization, use of data x, y, z to find the value of the geometric centroid of each triangle, then look for the centroid of the five
Accelerometer and gyroscope measurement as an inputs for Fuzzy Controller. Accelerometer given the orientation of Quadrotor and gyroscope given the rate of rotation. Accelerometer sensor MMA7361 and gyroscope GS-12 produce a Pulse Width Modulation (PWM) voltages. Output of this T1-Fuzzy and T2-Fuzzy is deltaSpeed which would be added to a present motors speed. A completed Fuzzy controller structure for this design shown in Figure 11. The desired points for each sensors taken in flat conditions.

Figure 10. Geometric Polyhedron with Five Areas

Figure 11. Fuzzy Controller System Design

Figure 12. Input Membership Function of T1-Fuzzy Sets

Figure 13. OMF of T1-Fuzzy
Rotation input has five labels Input Membership Function (IMF), and also Rate of Rotation input has five labels IMF too. The labels of IMF are Very Negative VN, Negative N, Zero Z, Positive P, Very Positive VP. Labels and values two inputs presented in figure 12. A model IMF using trapezoidal-triangle T1-Fuzzy Sets. For simplify process, in this design use a singleton OMF model with OMF labels are Very Decrease (VD), Decrease (D), Stay (S), Increase (I), Very Increase (VI) shown in Figure 13. T2-Fuzzy IMF designed only has three labels Input Membership Function (IMF) for Rotation to simplify array processing, and also Rate of Rotation input had three labels IMF. The labels are Negative (N), Zero (Z), Positive (P). Labels and values two inputs shown in Figure 14. A model IMF using trapezoidal-triangle T1-Fuzzy Sets. And then Output Membership Labels (OMF) labels are Decrease (D), Stay (S), Increase (I) shown in Figure 15.

Rules in inference block very important to make sure that Quadrotor BLDC motor very responsive toward a rotation and rate of rotation changed. In this system, there is only one possibility of control state shown in Figure 18. Two of beginning data taken before flight in base land/ground, this data called an initial data. After got the initial data, the closed-loop fuzzy controller process runs. Three kinds of state which looping until the Quadrotor off are get a new data from accelerometer and gyroscope sensors, do fuzzy controller process, and update a motor’s speed value.

To avoid Quadrotor broken, test-bed model used in this research. The test-bed model we used been illustrated in figure 19. Payload positions can be defined through Center of Gravity (COG) of Quadrotor. COG instrument builds in this design and also makes important thing to make validity of COG changes. COG instrument construct from four popular load-cells attached in diagonal form. The body of COG instrument uses alloy materials with dimension 67.5 x 80 cm shown in Figure 20. Visual display
(Figure 21) in the laptop must be provided to see the COG results. We can know the COG changed from dot-points change from the center of the grid view. This visual display using Delphi 7 Lite programming with Wi-FI communication between main control in COG instrument to laptop.

Figure 18. Design Flow State Controller

Figure 19. Quadrotor Test-Bed

Figure 20. COG Instrument Mechanic

Figure 21. Visual COG Instrument

Experimental Results

In this experiment, battery used as a payload. Battery did not bring into fix place at Quadrotor but its set in flexible positions. The payload positions changed in four variations; in center position, ¼, ½, and ¾ length of arm length Quadrotor. In that variation, the COG measure about 0 until 1.5 cm which 0 cm means the COG exactly at the center of Quadrotor and 1.5 cm where the payload position at ¾ of arm length Quadrotor. In this paper, motors speed becomes a focus to analyze with payload position variations as an output of T1-Fuzzy controller. After Quadrotor flight stable a few seconds, a disturbance applied to Quadrotor with touch down around 5 cm and released. The T1-Fuzzy controller worked to get a stable position as soon as possible with minimum oscillation.

Experimental results are shown in Figure 22, Figure 23, and Figure 24. In each figure shown for two sensors output, and motors speed responses for T1-Fuzzy (top) and T2-Fuzzy (bottom).
We can discuss about two focus, first we discuss about an oscillation events produced by T1-Fuzzy and by T2-Fuzzy. Second, we discuss about motors speed or motors responses. If we talk about an oscillation events, T2-Fuzzy gave better results than T1-Fuzzy in every COG variation. T2-Fuzzy have an oscillation less than T1-Fuzzy. A number of oscillations of T2-Fuzzy around 2 and 3 oscillation with the second oscillation very low and almost the same with the target point.

The results very clearly look that T2-Fuzzy most robust than T1-Fuzzy in these systems when we analyze about motors speed responses. Motors speed response when T1-Fuzzy applied always has an oscillation with varying speeds. Difference with T2-Fuzzy, the motor's speed have an oscillation in the beginning and after that very fast turning to stable speeds. In the visual observation, T1-Fuzzy have 6 until 10 oscillation movements before getting stable, but in T2-Fuzzy only have 3 until 4 oscillation movement before getting stable. It is clearly looking that T2-Fuzzy make the systems getting a stable very fast after got the disturbance.

![Figure 22. Comparison T1-Fuzzy and T2-Fuzzy Responses at 0 cm of COG](image-url)
Figure 23. Comparison T1-Fuzzy and T2-Fuzzy Responses at 0.5 cm of COG

Figure 24. Comparison T1-Fuzzy and T2-Fuzzy Responses at 1 cm of COG

Conclusion

A new robust T2-Fuzzy control method applied to H-Quadrotor 1-axis has been presented in this paper. Stabilizing Quadrotor with variant payload positions under...
manual disturbance as one of the problem in this work. A T2-Fuzzy controller design using a three IMF for two inputs and also three OMF for an output with Fast Geometric approach for defuzzification process. Any experiments using Quadrotor 1-axis in a test bed to reduce a damage factor.

Two models control T1-Fuzzy and T2-Fuzzy applied in Arduino Board and each control supplied with 3 model payload positions. The payload position gave a COG movement validating by COG instrument use 4 load cells. The results showed that T2-Fuzzy with simple IMF and rules better than T1-Fuzzy. T2-Fuzzy getting stable very fast after got their disturbance in a variation payload position which surely a COG has a variation values too. Using T2-Fuzzy as a controller will be getting a better flight efficiency because with this control the motor's speed did not have a gap in speed variations. In the future, we will research 2-axis Quadrotor to create the flight controller with high stability

Reference


