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Fuzzy Logic in Drone Control

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Abstract — **In this paper, we examine altitude and attitude stabilization of an unmanned aerial vehicle (UAV) using Fuzzy Logic. There are numerous types of UAVs, but the model analyzed in this paper is designed for a quadrotor micro aerial vehicles with mass no greater than 0,1 kg. A fuzzy logic controller with two inputs (errors and derivative errors) and a fuzzy output is designed in order to stabilize the roll, pitch and yaw angles and the altitude of a drone with four rotors. Since MATLAB is a well developed and commonly used platform by mathematicians and engineers, it was used for building the Fuzzy model. After the creation of appropriate membership functions and a 3x3 table of if-then rules, centroid method was used for the outputs defuzzification and the Mamdani model was tested in Simulink. In addition, a slight perturbation was applied to observe the robustness of this controller during hovering. The model showed a good and stabilized flight control scheme for a quadrotor, even if it is affected by perturbation.**

Keywords: UAV, Quadrotor, Fuzzy Logic Controller, MAV

1 INTRODUCTION

Quadrotor is a drone with four rotors that are directed upwards and placed in a square formation with equal distance from its center. Many quadrotor drones have been developed in the recent years and they differ in size and purposes, such as: Mini drones, Hobby drones, Selfie drones, racing drones and proportional drones. Mini drone or Micro Air Vehicle (MAV) got attention due to its small size with mass less than 0,1 kg, but also due to its durability and autonomous ability. Quadrotor is a typical design for small unmanned aerial vehicles because of its simple structure. It is controlled by adjusting the angular velocities of the rotors which are spun by electric motors. Since the quadrotor has six degrees of freedom (three translational and three rotational) but only four control inputs (the speeds of the four motors), it is an underactuated aerodynamic vehicle whose controlling can be a difficult task. [4] As a result, the robust autonomous flight capability is required for a quadrotor to accomplish the desired tasks. In general, quadrotors are inherently unstable systems, therefore, stabilization control is required. The purpose is to maintain its stability during maneuver, therefore a suitable control strategy is needed. Various control methods have been proposed to control the quadrotor: sliding mode control, PID & LQR control, Feedback Linearization, Backstepping control. However, this paper focuses on Fuzzy Logic controller for stabilization of a micro aerodynamic vehicle. Since the fuzzy logic controller (FLC) is one of the most popular strategies for addressing nonlinear dynamic uncertainties and a quadrotor is defined by a set of nonlinear equations, fuzzy logic is a good method for stabilizing a mini drone.

2 UNMANNED AERIAL VEHICLE

Unmanned Aerial Vehicle (UAV) is defined as an aircraft without the onboard presence of a human pilot. UAVs can be remotely controlled by a human operator or they can fly autonomously. [1]

The application of UAVs is diverse, such as in military, crop monitoring, coast watch, mineral exploration, telecommunications or ground traffic control. One of the biggest reasons for the widespread use of drones is their ability to traverse and maneuver through areas that would be dangerous for humans to be in. Apart from taking on dangerous tasks, drones can also monitor areas that do not necessarily pose a risk to human workers. Still, the reliance on human workers can add a considerable margin of error and accuracy.

UAVs come in various sizes. Large UAVs may be used alone in missions while small ones may be used in formations or swarms. The latter ones are proving to be quite useful in civilian applications. Drone automation shows a potential for reducing this risk of error. But even though UAVs have become increasingly complex and efficient by using the latest advancements in technology, there is still a chance for enhancement.

2.1 History

The earliest recorded use of an unmanned aerial vehicle for warfighting occurred in July 1849. using a balloon carrier. [2] In 1915, Nikola Tesla wrote about unmanned aerial combat vehicles. The first attempt at a self-propelled drone as an aerial target was completed in 1916 by A.M. Low. It wasn't until World War I that the first pilotless torpedo was invented by the Dayton-Wright Airplane Company. During World War II both Allied and German forces used drones as an aid in missions and trainings. After the end of World War II, drone developers began using jet engines in technologies like the Australian GAF Jindivik and the Model 10001, built for the U.S. Navy by Beechcraft. Even though drones were used 150 years for military research, the first use of non-military purposes was in 2006 when the Federal Aviation Administration issued its first commercial drone permit. After 2013, drones were also available to citizens, who most oftenly use them for commercial purposes and for recording panoramic views.

3 FUZZY LOGIC

Fuzzy logic is similar to a human being's feeling and inference process. Unlike classical control strategy, which is a point-to-point control, fuzzy control is a range-to-range control. The inputs and outputs of the controller are the same as the classical techniques, so the input is the error in the controlled variable, and the output is the control magnitude. However, the output of a fuzzy control is derived from fuzzification of both inputs and outputs using the associated membership functions. A crisp input, based on its current value, will be converted into different members of the associated membership functions. From this point of view, the output is based on its membership in different membership functions, which can be considered as a range of inputs.

Implementation of a fuzzy logic technique to real life problems requires four main steps:

1. Fuzzification – refers to the process of transforming crisp values into grades of membership using linguistic terms of fuzzy sets. The membership of each function is determined by a predefined fuzzy rule, which represents the fuzzy logic.

2. Fuzzy rule base – a component based on if-then rules. Fuzzy rule base will consider how to react with an input.

3. Inference – applies fuzzy rule base to the fuzzy outputs. After consideration of fuzzy rule base, an inference engine will provide an output and pass this output to defuzzification.

4. Defuzzification – a method to obtain mathematical data from the output of fuzzy rule base. In other words, it provides the final output of the fuzzy controller. [3]

A fuzzy control system primarily refers to the control of processes through fuzzy linguistic descriptions. More precisely, it is a mathematical system that analyzes analog input values in terms of logical variables. The advantages that the fuzzy logic has over neural networks and genetic algorithms are that the solution to a particular problem can be realized in terms that human operators can understand and their experience can be used to design the controller's if-then rules. The main benefit of fuzzy control is introducing clarity to the development, evaluation and maintenance of a control system.

A special class of control problems is control of highly nonlinear processes that are exposed to strong influences of external disturbances. Such systems are controlled by operators using their years-long experience and knowledge about static and dynamic characteristics of the system. The achieved quality of control is usually proportional to the operator's knowledge. The operator's experience is connected to monitoring relevant process variables, and depending on their states and deviations from reference values, operators decide where, how, and how much they need to act on the process to achieve a given control goal using the if-then rules.

3.1 History

Since the release of MATLAB and its graphical interface Simulink by Mathworks, inc. as a commercial product in 1984, the model design and simulation capabilities of MATLAB have been widely used and developed across several engineering and science disciplines. MATLAB and Simulink are currently used for various engineering implementations, education, research and development. In this paper, MATLAB and Simulink are used to build a fuzzy control system which will bring the drone to a still state without large oscillations.

3.2 MAV modeling

Quadrotor UAV is described by certain dynamic equations. The quadrotor vehicle operates on the concept of variable torques and thrusts. The quadrotor motors are arranged symmetrically in pairs along the horizontal and vertical axes with the forward pair rotating clockwise and the horizontal pair rotating counter-clockwise. This design results in the reaction torques from the pairs of motors being exactly opposed by each other if they are all spinning at the same speed. The elimination of the rotating moment (anti-torque) allows the vehicle to maintain a constant heading while hovering. Yaw is controlled by varying the speeds of the pairs of motors to create a non-zero net counter torque. Altitude is controlled by varying the thrust from each motor by equal amounts to provide a net thrust vector and without a rotational moment. To move in the lateral directions, the relative speeds of each motor in the lateral pair are varied to create a desired lateral thrust offset. The simple design results in small platforms which are battery operated, able to perform a stable hover, and safe to use in indoor environments. [4] Figure 1and 2 shows a form of a quadrotor.

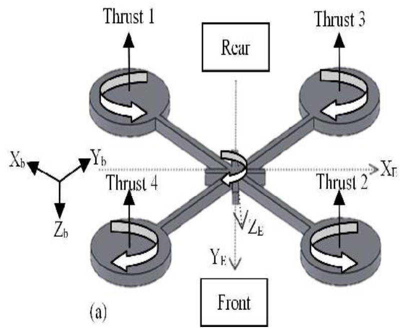

Figure 1: Quadrotor

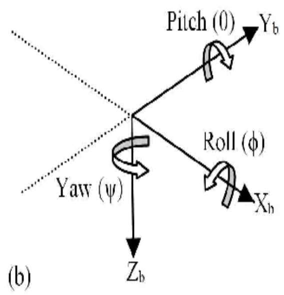

Figure 2: Quadrotor

Translational dynamics consists of three following equations that represent the acceleration of x, y and z. MAV altitude is defined by the equation of coordinare z.

$$\ddot{x} = \frac{U_1}{m}\left(S\psi S\phi + C\psi S\theta C\phi \right) \qquad (1)$$

$$\ddot{y} = \frac{U_1}{m}\left(-C\psi S\phi + S\psi S\theta C\phi\right) \quad (2)$$

$$\ddot{z} = g + \frac{U_1}{m}\left(C\theta C\phi \right) \qquad (3)$$

The attitude, i.e. the angular position of the quadrotor, is defined in the inertial frame with three Euler angles. Pitch angle θ determines the rotation of the quadrotor around the y-axis. Roll angle ϕ determines the rotation around the x-axis and yaw angle ψ around the z-axis. Following are the rotational equations, or angular rate of roll, pitch and yaw.

$$\ddot{\phi} = \frac{1}{I_{xx}}\left(\left(I_{yy} - I_{zz}\right)\dot{\psi}\dot{\theta} - (J_r\Omega_d)\dot{\theta} + lU_2\right) \qquad (4)$$

$$\ddot{\theta} = \frac{1}{I_{yy}}\left(\left(I_{zz} - I_{xx}\right)\dot{\psi}\dot{\phi} - (J_r\Omega_d)\dot{\phi} + lU_3\right) \qquad (5)$$

$$\ddot{\psi} = \frac{1}{I_{zz}}\left(\left(I_{xx} - I_{yy}\right)\dot{\theta}\dot{\phi} + U_4\right) \qquad (6)$$

In the equations (4), (5) and (6), *m* is the mass, *g* is the gravitational coefficient, *l* is the lateral arm length, and U_1 is the total thrust force generated by four rotors. *I* is the moment of inertia for the quadrotor, the diagonal matrix 3-by-3 is defined as *I* = diagonal$\left[I_{xx}I_{yy}I_{zz}\right]^T$, J_r is the rotor inertia, and Ω_d is the total rotor speed generated from the two pairs of rotors. Total torque is represented by U_2, U_3 and U_4. [5]

3.3 Control design

Fuzzy logic is designed to control MAV during hovering and attitude stabilization. The variables z, roll (ϕ), pitch (θ) and yaw (ψ) are used as a feedback response and four dedicated Fuzzy logic controllers are designed to control each state. The errors (e) and its derivatives (de) are used as fuzzy controller inputs in order to generate required outputs for the stabilization of the MAV. In addition, an integral feed forward is applied to improve steady state of the response signal. The controller architecture used in this paper is illustrated in Figure 3.

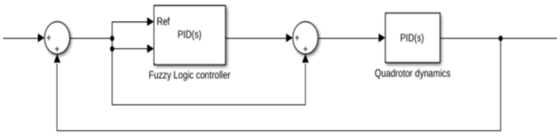

Figure 3: Simulink model

In this Mamdani fuzzy model, three membership functions are created for the error and derivative of the error. The error and derivative error are set to normalize at range $[-2, 2]$. The first input (error) has three membership functions: two Gaussian functions and one triangular function. The second input (derivative error) has three Gaussian membership functions. The linguistic variables used for error and derivative error are negative, zero and positive.

Five membership functions are created for the output to cover more areas during centroid methods of defuzzification. Three of output membership functions are triangular, and two of them are Sigmoid type functions. The range for the output is normalized at $[-10, 10]$. The linguistic variables used for the output are slow down, fast down, hover, slow up and fast up. Figures 4, 5 and 6 show the membership functions developed for the error, derivative error, and output, respectively. Figure 7 shows the output of the Mamdani model.

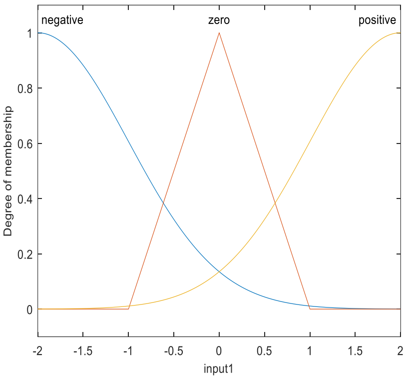

Figure 4: E input membership functions

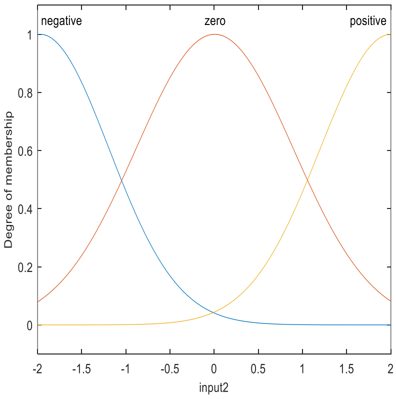

Figure 5: De input membership functions

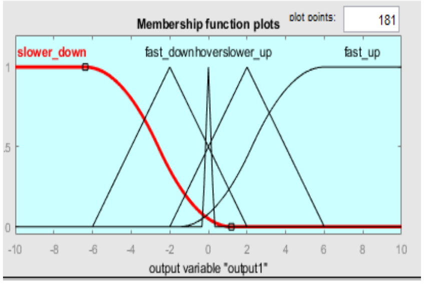

Figure 6: Output membership functions

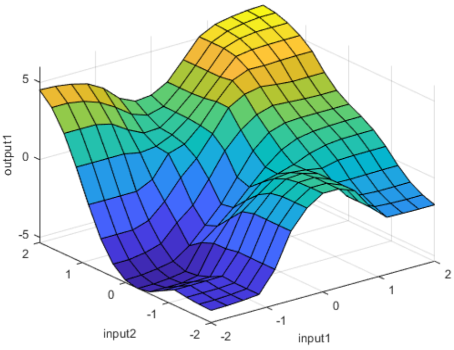

Figure 7: 3D output of the Mamdani model

A 3x3 table of if/then rules is created. For instance, if error is zero and derivative error is zero, then the drone should hover. The number in the bracket is a weightage set for the fuzzy engine to determine probability of which rule needs to be active in case there are two set of rules developed.

Table 1: Table of rules

e de	NEGATIVE	ZERO	POSITIVE
NEGATIVE	Fast down (0.5) Slower down (0.5)	Slower down (1)	Hover (0.5) Fast down (0.5)
ZERO	Slower down (1)	Hover (1)	Slower up (1)
POSITIVE	Hover (0.5) Fast up (0.5)	Slower up (1)	Fast up (1)

4 SIMULATION RESULTS

To verify the reliability and robustness of the Fuzzy controller, the quadrotor model is simulated in MATLAB Simulink. A few tests were conducted in order to evaluate the performance of the designed fuzzy controller. Integral absolute error (IAE) is chosen as the index performance.

Initially, the quadrotor is set at [0, 0,1, 0,1, 0,1] and [−2, 0, 0, 0] for z, φ, θ, and ψ, respectively. The gains were manually tuned to obtain satisfactory results and settling times. The simulation results presented in Figures 8 and 9 demonstrate the satisfactory performance of the proposed Fuzzy Logic Control system. In the simulation, for the altitude control, the settling time to reach 2 m is about 4 s.

In the attitude control, the settling time is about 1 ms, 2 ms, and 0,64 ms for roll, pitch, and yaw, respectively. The integral absolute error (IAE) for the case without perturbation for the altitude *z* is 4,6 and about 0,07 for the attitude. Meanwhile, for the case with perturbation as shown in Figures, the IAE increases to 5,4 with a small error for the altitude but it remains the same for the attitude. These results demonstrate a good performance of the Fuzzy Logic controller for a small-scale quadrotor.

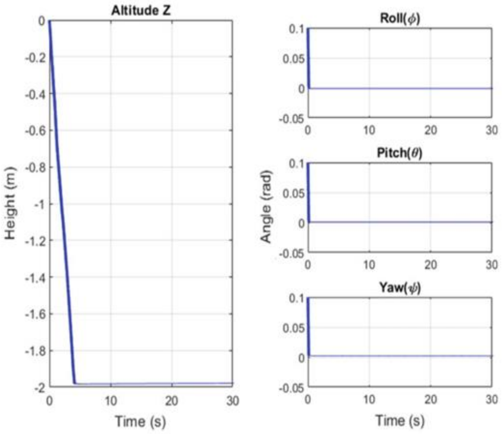

Figure 8: Altitude and attitude control using the Fuzzy controller

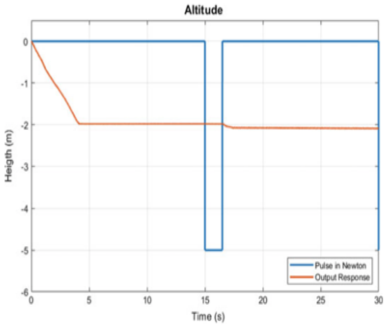

Figure 9: Altitude with slight perturbation using the Fuzzy controller

5 CONCLUSION

Fuzzy Logic has many useful applications in transportation, electronics, business and finance, defense, medicine, etc. In this paper, we examined the use of Fuzzy Logic in drone control. A Fuzzy Logic controller with 3x3 membership functions was proposed for the stabilization of a quadrotor micro aerial vehicle during hovering and movement. The simulation of the proposed Fuzzy Logic Control system was conducted in a MATLAB Simulink environment, where the results demonstrated an acceptable performance without or with perturbation applied on the altitude (z) and attitude (roll, pitch and yaw angles) of the quadrotor. Fuzzy Logic proved to be a good method for drone stabilization, however, better results can be achieved by developing different types of Fuzzy models or using other membership functions in the proposed model. Even though today's aerial vehicles are well developed and stabilized, there are still ways to improve using new technologies.

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