Quadrotor Unmanned Aerial Vehicle Control Techniques and Applications

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Abstract— **This paper presents a detailed evaluation and discussion of the controlling task of Quadrotor - Unmanned Aerial Vehicle (UAV). Related works based on the most common known control technologies for quadrotors and their achievements and applications in different areas are evaluated. Besides, this work will also explore an explicit procedure to design a PID controller programmed on STM32 microcontroller for stabilizing Quadrotor. The performances of this control system are going to be demonstrated by not only simulations but also experimental results. Lastly, future research directions are suggested.**

Index Terms— Quadrotor, Unmanned Aerial Vehicle, UAV, PID, STM32 microcontroller.

I. INTRODUCTION

With the development of science and technology, unmanned aerial vehicles (UAVs) or drones have attracted great attention of many researchers due to their wide applications, such as search and rescue operations, forest fire detection, construction and infrastructure inspection, crop management and monitoring, the delivery of goods, military surveillance and so on. There are many standards to classify the UAVs based on the large range of weight and size, function, kind of wings, altitude... Generally, they are categorized into four types: fixed, rotary, and flapping-wing aircraft, and hybrid aircraft [1].

All rotary-wing UAVs can perform hovering flight, the flight velocity is therefore highly adjustable, leading to excellent flexibility and maneuverability. Quadrotor is the most popular configuration of rotary-wing UAVs, it is lifted and thrust by four fixed rotors. The rotational speeds of four rotors are independent, so it's possible to control the roll, pitch, and yaw attitude of the vehicle.

Quadrotor has a relatively simple design but the controlling task for a quadrotor is not easy because the quadrotor dynamics are highly non-linear and some parameters such as the aerodynamic coefficients and inertial moments, which are related to the dynamic model, cannot be measured or obtained exactly [2]. In addition, the quadrotor is very sensitive to external disturbances from environments due to its weight and size. Thereby making its flight control more complex. This has led to several control methods proposed in the current literature.

In this work, the focus is a review of the prominent controllers applied to the quadrotor and then a detailed experiment of digital PID controller for stabilizing quadrotor implemented on STM32 microcontroller.

The rest of this paper is organized as follows: Section 2 provides the brief descriptions of the mechanism and dynamics of a quadrotor; Section 3 gives a survey of flight control algorithms; In Section 4, the simulations, experimental setups, and results of the controller for stabilizing quadrotor are presented and the conclusions are given in Section 5.

II. PRELIMINARIES

A. Quadrotor mechanism

Quadrotor is lifted and propelled by four rotors. The rotors have an equal distance to the center of mass of the quadrotor in a square formation. Two propellers (number 1, 3) rotate clockwise and two others rotate counter-clockwise (number 2, 4). To move to the desired trajectory, the flight speed and direction changing are achieved by modifying the angular velocity of each rotor (Figure 1). When the quadrotor rotates in the horizontal plane, it causes yaw motion. It means that if the moments generated by one pair differ from the other pair, it will cause yaw motion.

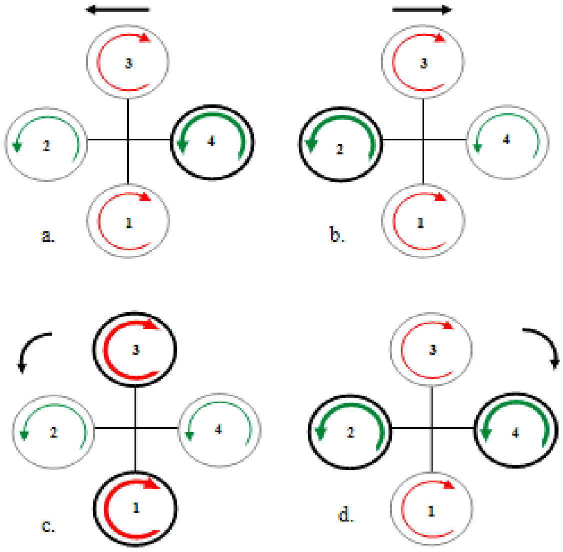

Figure 1 Movement of quadrotor due to rotor speeds

B. Quadrotor dynamics

Figure 2 shows quadrotor frame system with a vehicle frame (x,y,z).

The forces and moments on quadrotor are calculated by equations (1), (2), (3).

$$F_i = k_f \omega_i^2 \,;\; M_i = k_m \omega_i^2 \tag{1}$$

$$M_x = \left(F_1 - F_2\right) l \,;\; M_y = \left(F_2 - F_4\right) l \tag{2}$$

$$\mathrm{w} = mg \tag{3}$$

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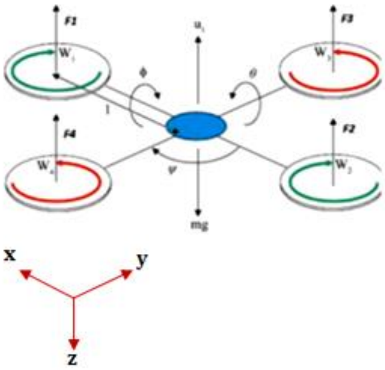

Figure 2: Diagram for quadrotor frame system.

The motion of the quadrotor can be analyzed by applying Newton's second law. For linear motion, forces are calculated as a product of mass and linear acceleration, and torque is estimated as a product of inertial and angular acceleration in the rotational motion.

Three conditions should be considered to control the quadrotor: Rising condition, hovering condition, and landing condition. In the rising condition known as take-off mode, the total force must be greater than the weight of the quadrotor, and all moments should be also zero.

$$mg < \sum F_i = F_1 + F_2 + F_3 + F_4 \tag{4}$$

The equation of motion in the case of the rising condition as (5).

$$m\ddot{r} = \sum F_i - mg > 0 \text{ or } F_1 + F_2 + F_3 + F_4 - mg > 0 \tag{5}$$

In landing mode, the total force must be less than the weight of the quadrotor, and all moments should be also zero.

$$mg > \sum F_i = F_1 + F_2 + F_3 + F_4 \tag{6}$$

The equation of motion in the case of the landing condition as (7).

$$m\ddot{r} = \sum F_i - mg < 0 \text{ or } F_1 + F_2 + F_3 + F_4 - mg < 0 \tag{7}$$

The hovering condition means how the quadrotor hangs on the air, in this condition total force should be balanced or the total force produced by four propellers is equal to gravity force, and all moments produced are zero.

$$mg = \sum F_i = F_1 + F_2 + F_3 + F_4 \tag{8}$$

The equation of motion in the case of the hovering condition as (9).

$$m\ddot{r} = \sum F_i - mg = F_1 + F_2 + F_3 + F_4 - mg = 0 \tag{9}$$

When the quadrotor rotates in the horizontal plane, it causes yaw motion. In other words, if the moments generated by one pair differ from the other pair, it will cause yaw motion. The yaw motion of quadrotor is described by the following equation,

$$I_{zz}.\ddot{\psi} = \sum M_i \tag{10}$$

Similar to yaw motion, we can obtain roll and pitch motion when the quadrotor rotates around x, and y axis respectively.

$$I_{xx}.\ddot{\phi} = (F_3 - F_4)l; \tag{11}$$

$$I_{yy}.\ddot{\theta} = (F_1 - F_2)l \tag{12}$$

Hence, the equations of quadrotor motion as following,

$$I_{xx}.\ddot{\phi} = k_f l\left(\omega_3^2 - \omega_4^2\right) \tag{13}$$

$$I_{yy}.\ddot{\theta} = k_f l\left(\omega_1^2 - \omega_2^2\right) \tag{14}$$

$$I_{zz}.\ddot{\psi} = k_m.\left(\left(\omega_1^2 + \omega_2^2\right) - \left(\omega_3^2 + \omega_4^2\right)\right) \tag{15}$$

In which,

- F stand for forces and M index stand for moments.
- M_x and M_y: Moments along the x-axis and y-axis, respectively.
- l : length of the arm holding propellers (length from the rotor to the center of the frame)
- w : gravitational force caused by weight.
- m : total weight of the quadrotor
- I_{xx} : Moment of inertial along x-axis, y-axis, z-axis, respectively.
- k_f : Thrust (lift) factor
- k_m : Drag factor

III. SURVEY OF FLIGHT CONTROL ALGORITHMS

Due to the nature of the quadrotor dynamics, several control algorithms have been applied. Each control method has its advantages and disadvantages. The control methods used could be broadly categorized as linear and non-linear control schemes. In this section, the prominent controllers applied to the quadrotor within these categories are presented.

A. *Linear flight controllers*

PID controller: The classic PID control is a simple structure with high stability, which can use to control the quadrotor. Main controlling tasks are stabilizing and hovering motion, good performance, and robustness [3]–[5]. However, a quadrotor flies in a rugged environment, a classic PID is no longer relevant. So, some researchers have improved the PID algorithm to tackle uncertainties and external disturbances. The novel PID controllers are optimized by adding intelligent algorithms such as particle swarm optimization (PSO), fuzzy logic to improve dynamic performance [6]–[8].

LQR controller: Linear Quadratic Regulator algorithm operates a dynamic system by minimizing a suitable cost function. The LQR usually utilizes missing information and noise conditions to perform the quadrotor flight control [9]–[10]. The advantages of this approach are good disturbance rejection, high stability but it has low performance in the presence of many obstacles.

H∞: This controller is the widely used robust controller to deal with problems of uncertain parameters and external disturbances encountering the flight process of the quadrotor [11],[12].

B. *Non -linear flight controllers*

Backstepping controller: Backstepping control is a well-known recursive algorithm of general nonlinear control systems, the main idea of this method is breaking down the controller into steps and progressively stabilizes each subsystem. Its advantages are that the algorithm converges fast and it can tackle disturbances well while the disadvantage is poor robustness [13]-[15].

Sliding mode controller: This is an easily applicable nonlinear control method that implements by applying a discontinuous control signal to the system to command it to slide along a prescribed trajectory [16],[17]. Its advantages are low sensitivity to external disturbances, rapid response, and good tracking ability.

Adaptive controller: This approach is aimed at adapting to parameter changes in the systems. In other words, this method is a robust and effective technique for systems having unmodeled dynamics and parametric uncertainties. It can handle the trajectory tracking problem of the quadrotor under fault conditions and produces better results as compared to other controllers [18]-[20].

IV. DESIGN A PID CONTROLLER FOR STABILIZING QUADROTOR

Stabilizing quadrotor is the first task before tracking along desired trajectories, and there are so many control strategies for balancing quadrotor in the air in which PID controller [21] is the most popular due to its convenience. PID functions to force the output of the plant to follow the expectation. There are three Euler's angles: roll, pitch, yaw, which should be taken into account in order to stabilize the quadrotor hanging on the sky.

In this section, the paper proposes a control scheme utilizing digital PID controllers for controlling each angle. The results will be proved by not only simulation but also experiment.

A. *Control scheme and Simulation*

Table 1: Parameters due to dynamics of quadrotor

Symbols	Values	Units
l	0.225	m
m	0.5	Kg
I_{xx}	4.856×10^{-3}	Kg.m^2
I_{yy}	4.856×10^{-3}	Kg.m^2
I_{zz}	8.801×10^{-3}	Kg.m^2
k_f	1.26×10^{-5}	
k_m	2.06×10^{-7}	

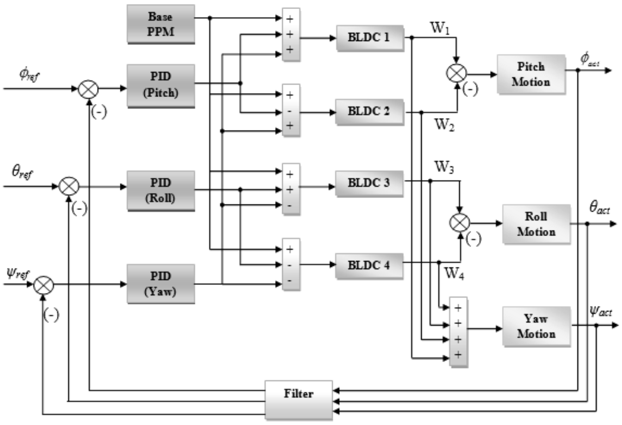

Figure 3: Control scheme for stabilizing roll, pitch, yaw angles

Controllers for roll and pitch angles:

The mathematical model due to roll angle can be calculated by the following equation

$$\phi = \left[\left(\text{Base PPM + U}_1\right)G_{BLDC} - \left(\text{Base PPM - U}_1\right)G_{BLDC}\right].G_{dyn}$$

Therefore the mathematical model due to roll angle will be archived as following:

$$G_\phi(s) = 2G_{BLDC}.G_{dyn} = G_\phi(s)$$
$$= 2\times\frac{118.91}{(0.1649s+1)(0.076s+1)}\times\frac{k_f.l.k_v}{I_{xx}.s^2}$$

By approximating $\omega^2 = k_v.\omega$, the transfer function will be:

$$G_\phi(s) = 2\times\frac{118.91}{(0.1649s+1)(0.076s+1)}\times\frac{k_f.l.k_v}{I_{xx}.s^2} \quad (16)$$

Equation (16) we can be rewritten:

$$G_\phi(s) = \frac{k_\phi\times237.82}{s^2(0.1649s+1)(0.076s+1)} \quad (17)$$

We can approximate (17) by (18)

$$G_\phi(s) = \frac{k_\phi\times237.82}{s^2(0.24s+1)} \quad (18)$$

The PD controller should be chosen in this case, because the plant has itself an integral part.

$$G_{PD}(s) = k_p\left(1+sT_d\right)$$

Due to the quadrotor has a symmetric construction, the pitch angle is the same as roll angle. The difference here is that the pitch angle is controlled by adjusting the speed of rotors 3 and 4. Therefore, the controller of pitch angle is also PD with the same parameters.

Controller for yaw angle:

The mathematical model due to yaw angle can be calculated by the following equation

$$\psi = G_E.G_{dyn}$$
$$G_E = \left(\text{Base PPM + U}_1\text{+U}_3\right) + \left(\text{Base PPM - U}_1\text{+U}_3\right)$$
$$-\left(\text{Base PPM + U}_2\text{-U}_3\right) - \left(\text{Base PPM - U}_2\text{-U}_3\right)$$
$$\Rightarrow G_\psi(s) = 4G_{BLDC}.G_{dyn}$$

$$G_\psi(s) = 4\times\frac{118.91}{(0.1649s+1)(0.076s+1)}\times\frac{k_f.l.k_v}{I_{xx}.s^2} \quad (19)$$

Equation (19) we can be rewritten:

$$G_\psi(s) = \frac{k_\phi\times475.64}{s^2(0.1649s+1)(0.076s+1)} \quad (20)$$

We can approximate (20) by (21)

$$G_\psi(s) = \frac{k_\phi\times475.64}{s^2(0.24s+1)} \quad (21)$$

Similar to roll and pitch angle's controllers, the PD controller should be chosen for yaw angle, because the plant has itself an integral part.

$$G_{PD}(s) = k_p\left(1+sT_d\right)$$

Discretization:

In order to implement this controller on STM32 microcontroller , we need to discrete the control signal.

$$u(t) = k_p + T_d \frac{d}{dt} e(t)$$

$$\underline{discrete} \quad u_{k+1} \approx k_p + T_d \frac{e_{k+1} - e_k}{t_{k+1} - t_k} \approx k_p + T_d \frac{e_{k+1} - e_k}{h} \qquad (22)$$

in which h is step size.

Simulation results: Before coming up with an experimental setup, simulation is a good process to avoid violence. Matlab/ Simulink tool is used. Figure 4 indicates the roll angle response when applying PD controllers for three Euler's angles. The continuous line indicates the reference value, and the dot line indicates the output response. The parameters of PD controller used in this simulation are kp=7.8, and Td=0.6.

Firstly, the roll angle is set to be zero, then changed to negative ten degrees at 15s. The output response verifies that the PD controllers provide good performance with a fast response and no steady-state error.

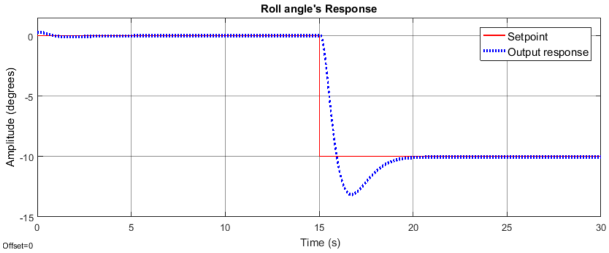

Figure 4: Roll angle's response.

B. *Experimental Setup*

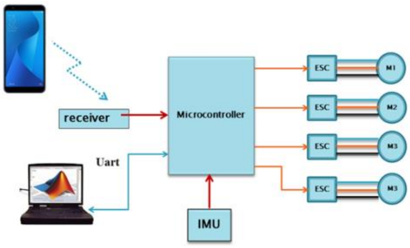

Figure 5: Experimental system block diagram.

In this experiment setup, the main circuit is designed for implementing real-time control [22], [23]. Figure 5 indicates that the main circuit has functions of receiving the command from a smartphone or laptop, then sends control signals to drive BLDCs.

The description of the complement filter for roll angle is given by (23):

$$\theta = \frac{1}{Ts+1}\theta_{accel} + \frac{Ts}{Ts+1}\frac{1}{s}\dot{\theta}_{gyro} \qquad (23)$$

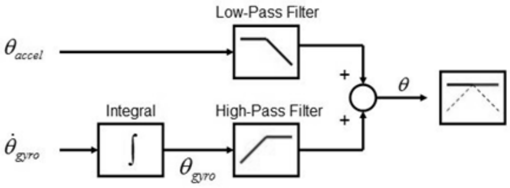

Figure 6. Complement filter structure

In the discrete domain the complement filter is presented by equation (24):

$$\theta(t_{k+1}) = \alpha\left(\theta(t_k) + h.\dot{\theta}_{gyro}(t_{k+1})\right) + (1-\alpha)\theta_{accel}(t_{k+1}) \qquad (24)$$

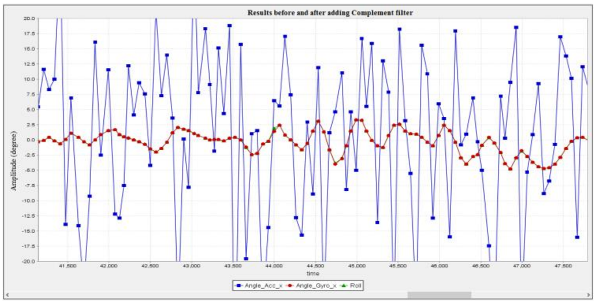

Figure 7: The roll angle's response before and after adding the complement filter.

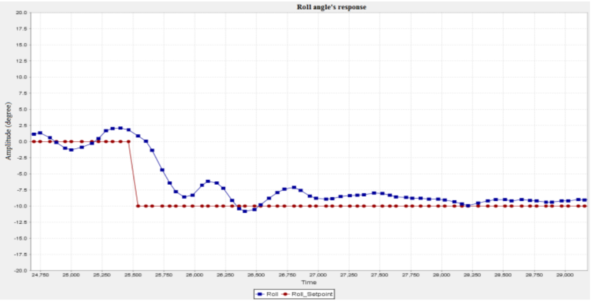

Figure 8: The roll angle's response on the experimental setup

The signal is less oscillated after adding the complement filter. The control feedback system works well when the feedback signal is precise. In Figure 8, the roll angle's response is indicated, the desired roll angle is set to be zero at the beginning, then changed to negative ten degrees at 25s. The roll angle's response follows the desired values after a short time.

V. CONCLUSION

This paper presents research about control techniques for the quadrotor-UAV and its applications. This work focuses mainly on the working principle of quadrotor physically, several common linear control and nonlinear techniques using on quadrotors in current literature, and then the construction of the flight control strategy utilizing digital PID controllers for stabilizing quadrotor. The results were proved by not only simulation but also experiment with a good performance. In the future, the quadrotor flight controller with the combination of learning-based control methods and computer science to process the motor parameters will promise to enhance system performance under different flight and mission conditions.

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