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International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

The Quadrotor MAV system using a double-loop PID control

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A R T I C L E I N F O

Article history:
Received 27 December 2015
Received in revised form
21 January 2016
Accepted 21 January 2016

Keywords:
Quadrotor
Robot control
PID control

A B S T R A C T

This paper discusses the design control method and improves the quality of control for a quadrotor Miniature Aerial Vehicles (MAV). In this research, we propose a double-loop PID controller with six control signals, so the quadrotor can move on a certain trajectory while maintaining specified speeds and orientations which gives this design superior maneuverability. A design controller method based on Matlab/Simulink has been presented, its result compared with a single-loop PID control approaches. The simulation results analysis in the perfect conditions without disturbances effectives, and the final is experimental results of real model. The simulation results and experimental results show the effectiveness of the proposed controller.

1. Introduction

In recent years, a quadrotor Miniature Aerial Vehicles (MAV) has received quite much attention of researchers and it has developed diverse about types and features. Because the ability to carry relatively large payloads, the Vertical Take Off and Landing (VTOL) capability and the high maneuverability, therefore quadrotor have many diverse application such as military reconnaissance, air searchs, television, photography, observing, adventure, construction, emergency rescue .

Making quadrotor is not an easy task for manufacturers because of its has complex structure, nonlinear dynamics properties and under-actuated nature, so with a target of achieving a high performance, control flight capability and control real-time system are the target which all makers notes.

Design control system for quadrotor relatively complex and choosing control algorithms is very an important issue. Nowaday, there are many way to control for quadrotor, that are PD/PID controller (Abdelhamid and Stephen, 2006; Salvador and Javier, 2010; Shahida et al., 2014; Atheer et al., 2010), Backstepping control (Erdinç et al., 2005), Sliding mode control (SMC) (Benallegue1 et al., 2008), Visual servoing (Odile et al., 2009), Linear quadratic regulator (LQR), Neuron network (Travis and Sarangapani, 2010), Adaptive control (Justin and Gang, 2014; Salvador and Javier, 2010; Swee et al., 2012). Active disturbance rejection control (ADRC). All of the control method above, PID control is a powerful control method and has also been used for the control of quadrotor. It has a simple structure, calculated not much, easy to control but high effect.

On researchs using PID controller in the above list, a close single loop PID control has been employed by almost researchers. Because it only has four variables (z, ϕ, θ and ψ) so this control method provides a systemic approach to the control of quadrotor position imprecision. To deal with this problem, in this paper, quadrotor MAV with six control variables (x, y, z, ϕ, θ and ψ) using a double-loop PID control has been presented, its structure has an outside loop with the position control and an inside loop with the attitude control. The control quality is improved quite much with this proposal, experimental results showed the proposed method has been effective.

The development in this research (Part2) augments the result developed in Part 1 (Minh et al., 2015) by considering a double-loop PID controller to replace a single-loop PID controller. This paper presents the control system design and experiments of a quadrotor system with double-loop PID controller. The rest of the paper is organized as follows. Section II discusses the quadrotor MAV structure and its dynamic system model. Section III illustrates a double-loop PID controller design. Section IV shows the parameters identification results and model verification through computer simulation. In section V, attitude estimation and flight experiments are provided to validate the proposed estimation algorithm and control strategy. Finally, the major conclusions of the paper are summarized in Section VI.

2. The quadrotor dynamic model

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The schematic of a quadrotor MAV in this paper is shown in Fig. 1. The four rotors are symmetrically distributed respect to the central cabinare denoted by Ω_1, Ω_2, Ω_3 and Ω_4 respectively. The inertial position of the quadrotor center of mass is denoted by (x, y, z) and attitudes signal as Roll, Pitch and Yaw denoted orientation of the quarotor.

The quadrotor system with 6 degrees of freedoms (DOFs), its movement in the body-frame Decade coordinates (x, y, z) and ϕ, θ, ψ are roll, pitch and yaw angles respectively. These angles indicate the rotation of x, y and z of the fixed frame.

This quadrotor MAV model has six outputs (x, y, z, ϕ, θ and ψ) while it only has four independent inputs, therefore the quadrotor is an under-actuated system. It is controlled by varying the angular velocity of the rotors. Front and back rotors rotate clockwise, meanwhile left and right rotors rotates anti-clockwise. This makes the balance moving and moves up and down easily (Yaw) when necessary.

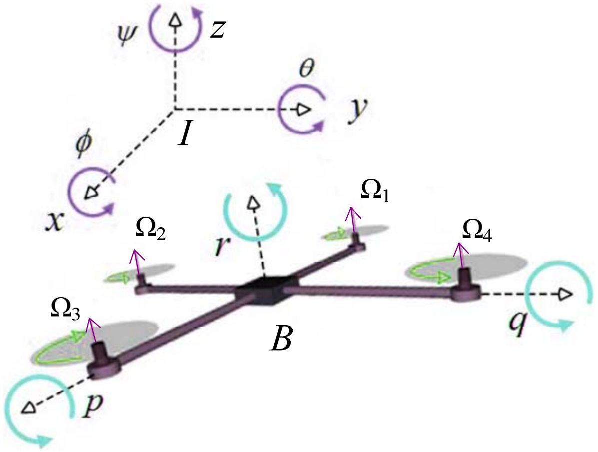

Fig. 1: Free body diagram of Quadrotor with geographical coordinate system representation

Let's define the rotation matrix ${}^IR_B$ which expresses the transformation from the inertial frame to the body frame (Abdelhamid et al., 2006; Nguyen et al., 2014; Atheer et al., 2010):

$$ {}^IR_B = \begin{bmatrix} c_\varphi c_\theta & c_\varphi s_\theta s_\psi - s_\varphi c_\psi & c_\varphi s_\theta c_\psi + s_\varphi s_\psi \\ c_\varphi s_\theta & s_\varphi s_\theta s_\psi + c_\varphi c_\psi & s_\varphi s_\theta c_\psi - c_\varphi s_\psi \\ -s_\theta & c_\theta s_\psi & c_\theta c_\psi \end{bmatrix} \quad (1) $$

where $S_\theta = sin(\theta)$, $C_\psi = cos(\psi)$, etc., and ${}^IR_B$ is the transformation matrix.

The mathematical model of the quadrotor MAV is driven using Lagrange approach and the simplified mathematical model has been presented in (Shahida et al., 2014; Norafizah et al., 2011) and the simplified form of differential equations of motion of modeled quadrotor as shown in below equation:

$$ \begin{cases} \ddot{x} = (\sin\psi \sin\phi + \cos\psi \sin\theta \cos\phi)\dfrac{U_1}{m} \\ \ddot{y} = (-\cos\psi \sin\phi + \sin\psi \sin\theta \cos\phi)\dfrac{U_1}{m} \\ \ddot{z} = -g + (\cos\theta \cos\phi)\dfrac{U_1}{m} \end{cases} \quad (2) $$

where m is the helicopter mass, g is the gravitational acceleration and control signals U is illustrated following below equation.

$$ \begin{cases} U_1 = b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2) \\ U_2 = bl(\Omega_4^2 - \Omega_2^2) \\ U_3 = bl(\Omega_3^2 - \Omega_1^2) \\ U_4 = dl(\Omega_2^2 + \Omega_4^2 - \Omega_1^2 - \Omega_3^2) \\ \Omega = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4 \end{cases} \quad (3) $$

where b is the lift coefficient, l is the distance from the motor center to the aircraft center, Ω_1, Ω_2, Ω_3 and Ω_4 denoted the four rotors speed, respectively.

3. The design of the double-loop PID controller

This section discusses the control system design based on a double-loop PID controller. We consider the traditional PID control structure described by equations of the form:

$$ u(s) = (K_p + \frac{K_i}{s} + sK_d)e(s) \quad (4) $$

where e denoted error of input and output, u denoted control signal, K_p, K_i, K_d denoted coefficient of gain, time integral, time derivative, respectively.

Fig. 2 presents a block diagram of the proposed control system. The system uses a double loop cascade PID controller. Inside loop is the attitude control loop, and outside loop is the position controller. The input to the attitude control loop is the output of the position control loop. The feedback of attitude control and position control comes from the inertial sensors.

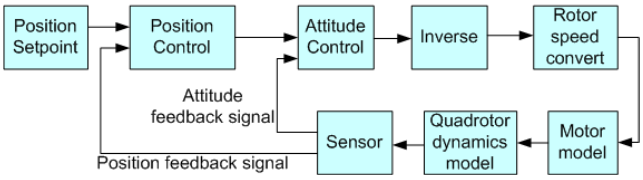

Fig. 2: The quadrotor control structure

In the outside loop, the desired position in coordinate (x, y, z) is compared with the measurement of the quadrotor producing the position error that is used in the position controller algorithm. The output of position control is compared with the measurement of the attitude of the quadrotor that is used in the attitude controller algorithm.

The Inverse block function is used to inverse value in following expression.

$$ \begin{cases} \ddot{z} = -g + (\cos\theta \cos\phi)U_1 / m \\ \ddot{\phi} = U_2 / I_x \\ \ddot{\theta} = U_3 / I_y \\ \ddot{\psi} = U_4 / I_z \end{cases} \quad (5) $$

where I_x, I_y and I_z denotes moments of inertia of the aircraft with respect to the axes.

After the equations in (5) are inversed, the control signals U_1, U_2, U_3 and U_4 we obtained as in the following formula:

$$\begin{cases} U_1 = (\ddot{z} + g)m / (\cos\theta \cos\phi) \\ U_2 = I_x \ddot{\phi} \\ U_3 = I_y \ddot{\theta} \\ U_4 = I_z \ddot{\psi} \end{cases} \qquad (6)$$

The input signals of Rotor Speed Convert block by using (6) and that block based on equation (3), the rotor speed signals are calculated as following

$$\begin{cases} \Omega_1^2 = \frac{1}{4b}U_1 - \frac{1}{2bl}U_3 - \frac{1}{4d}U_4 \\ \Omega_2^2 = \frac{1}{4b}U_1 - \frac{1}{2bl}U_2 + \frac{1}{4d}U_4 \\ \Omega_3^2 = \frac{1}{4b}U_1 + \frac{1}{2bl}U_3 - \frac{1}{4d}U_4 \\ \Omega_4^2 = \frac{1}{4b}U_1 + \frac{1}{2bl}U_2 + \frac{1}{4d}U_4 \end{cases} \qquad (7)$$

4. Simulation and analysis

4.1. Modeling for simulation

In this work, a double-loop PID control built in Matlab/Simulink environment has been presented, the internal functional blocks in this diagram are designed according to the algorithm in equations (2), (3), (5), (6) and (7). We consider a quadrotor simulator blocks diagram as follows.

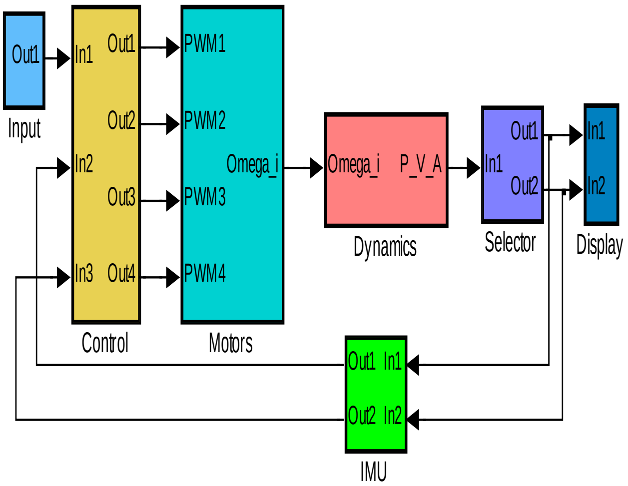

Fig. 3: Quadrotor simulator blocks diagram

We can see from the above block diagram, there are relatively similar about simulator structure between a double-loop PID controller in this paper and a single-loop PID controller in (Minh et al., 2015). However, it has some different as:

- Input Module is taken signals from different inputs. In this case, the input of the quadrotor is a reference signal with position (x_d, y_d, z_d).
- Control Module has inner structure different with Control module structure of a singer-loop PID control. This module will be analyzed in the next work.
- Selector Module used to select signal, the position parameter x, y, z and attitude parameter ϕ, θ, ψ from output of Dynamic Module becomes to input of IMU Module (Inertial Measurement Unit).
- Display Module used to display stability control system response of position (x, y, z) and attitude angles (ϕ, θ, ψ).

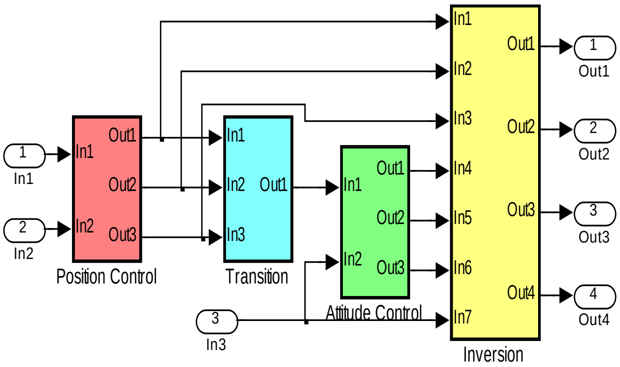

Fig. 4: Control blocks in quadrotor simulator

In the Fig. 4, the position controller with PID algorithm of this design consist of outside loop Position Control Module and Transition Module, its input is reference signal of MAV with Earth position x_d, y_d, z_d and measurement position from sensor x, y, z. The output of Position Control Module is calculated by Transition Module, it's given suitable changes for attitude angles to ensure that the error of its signal and the inside loop input is minimum. Attitude Module is the angular module control of MAV with PID algorithm. This controller used to calculate the signal between the output of Transition Module and measurement angular signal. Inversion Module used to convert the output of Position Control Module and Attitude Control Module to rotor speed control signal Ω_1, Ω_2, Ω_3 and Ω_4.

4.2. Simulation result and analysis.

In order to analyze the dynamic behavior of the proposed quadrotor vehicle and the proposed controllers, a simulation model has been developed in Matlab Simulink.

In this study, let quadrotor system fly from position O(0, 0, 0) to position A(0.1, 0.1, 1) and attitude angles are set as ϕ = 0rad, θ = 0rad, ψ = 0rad.

Ignore the effect of noise in the sensor, using Matlab/Simulink to simulate the MAV with a double-loop PID controller approach in the perfect conditions, after several rounds of testing, the optimal control parameters for each channel values as shown in Table 1.

Table 1: Double-loop control system simulation parameter value table.

	K_p	K_i	K_d
Roll	0.7	0.0	0.12
Pitch	0.7	0.0	0.12
Yaw	0.06	0.01	0.2
X	0.08	0.001	0.41
Y	0.08	0.001	0.41
Z	23.5	6.0	19.5

Fig. 5 to 10 shows the response of position x, y, z and angular ϕ, θ, ψ of the quadrotor MAV. It can be seen that three attitude angles driven to stabilise quickly after 5 seconds.

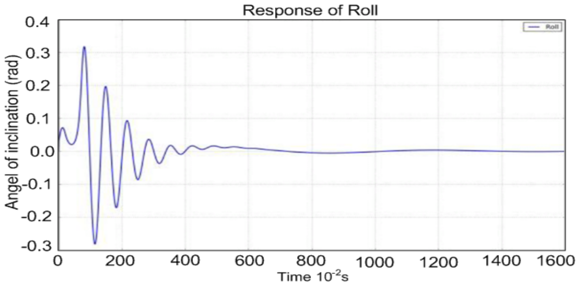

Fig. 5: Stability control system response of Roll

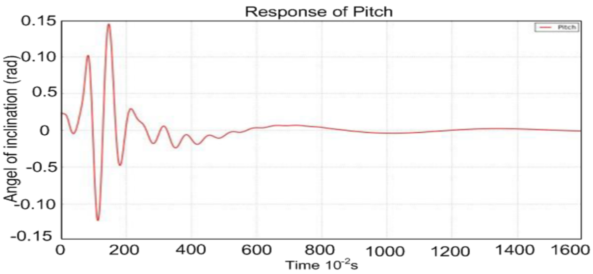

Fig. 6: Stability control system response of Pitch

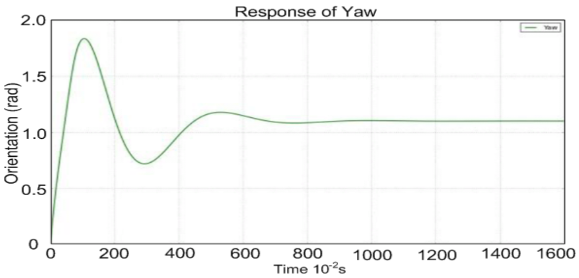

Fig. 7: Stability control system response of Yaw

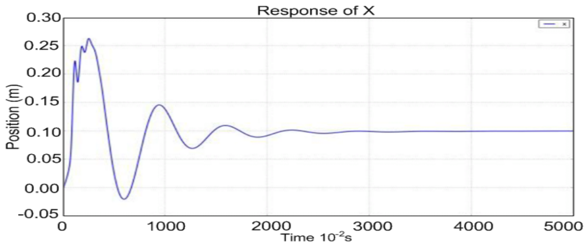

Fig. 8: Stability control system response of X

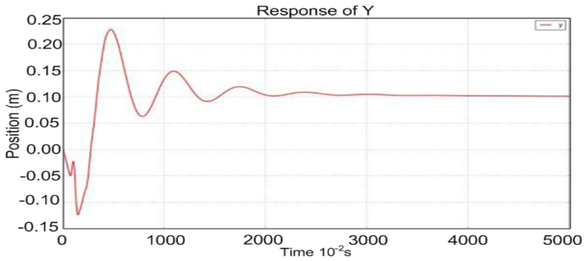

Fig. 9: Stability control system response of Y

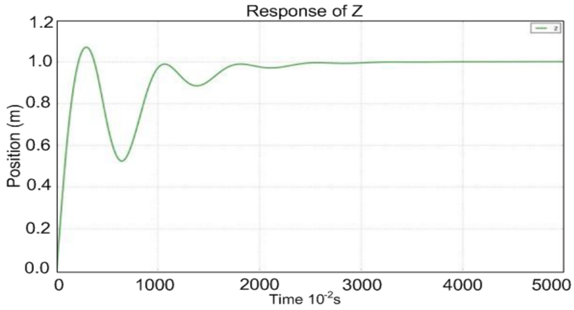

Fig. 10: Stability control system response of

From the simulation results, we can be seen that, quadrotor MAV fly from an initial position to require position and stable at that. When the MAV achieves stable position, the parameters of Roll, Pitch and Yaw angles are $\phi = 0$rad, $\theta = 0$rad and $\psi = 1.1$rad, respectively. Following this simulation results, responses of Roll and Pitch are not really good, large overshoot and chattering. While response of Yaw is better, after only 2 times chattering, a stable state of Yaw angle has been achieved. After chattering, output of quadrotor are x, y and z also achieve to require position and almost no error. However, the simulation result showed that the characteristics of x and y have long stability time and slow response. Because there are nonlinear dynamic properties between links of Roll, Pitch and Yaw angles. But the effects of this cause have been rejected when we design the control algorithms so the control effects are not yet perfect.

5. Testing the flight

After identifying all the quadrotor parameters and constructing the attitude estimation algorithm, their verification and testing are desired.

In order to flight testing have a good results and reject the effects of disturbances caused by the wind. The proposed quadrotor MAV approach has been implemented and tested in an indoor laboratory environment.

Fig. 11 to 13 shows the simulation experiment result of Roll, Pitch and Yaw angles, respectively.

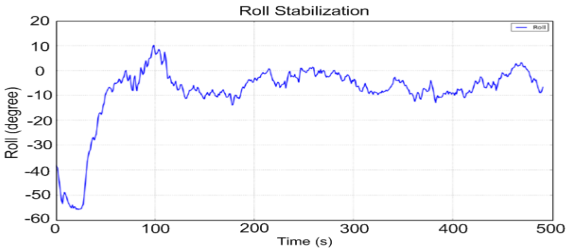

Fig. 11: Experimental response of Roll angle

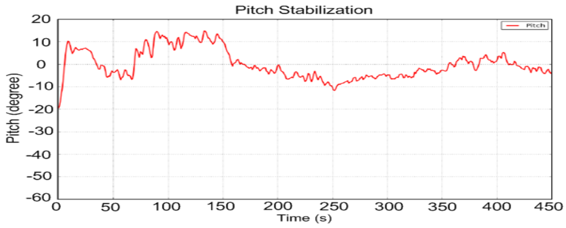

Fig. 12: Experimental response of Pitch angle

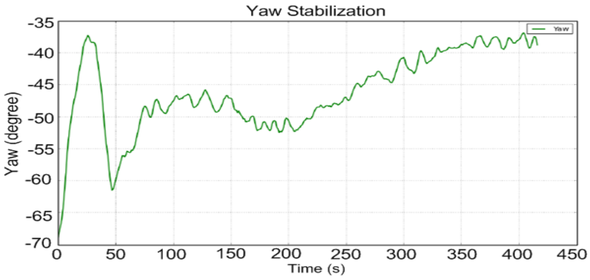

Fig. 13: Experimental response of Yaw angle

In this experiment, the reference angular of Roll, Pitch and Yaw are $\phi = -20^0$, $\theta = -38^0$ and $\psi = -68^0$, respectively. From the experimental results, the simulation shows clealy that only the responses of Roll and Pitch are the best, both of them driven to the stabilization at 0^0 quickly and the chattering deviations within $\pm 10^0$. Besides, the response of Yaw is not good, although it have small overshoot but response time is quite slow. However, it also driven to stabilization at -40^0 and the require control has been achieved.

This simulation results also can effectively verify the adaptive ability and robustness of the flight control system.

Fig. 14: Quadrotor MAV model and flight testing

6. Conclusion

In this paper, a double-loop PID controller design for a 6 DOFs quadrotor with 6 control variables (x, y, z, ϕ, θ and ψ) is proposed. The motion of the aircraft can be easily achieved by just tuning the speeds of the four rotors. The advantage of this method is easiest to exactly control the coordinate's fly of quadrotor. The numerical simulation results on the computer are provided to demonstrate the correctness and appropriateness of the design method. Experimental results showed that the model stable operation and easily controlled in a laboratory environment, which exactly demonstrates the situation discussed above. As a future work, modeling and double-loop PID control for this system after adding a disturbance by wind, payload, when flight outdoor will be considered.

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