Attitude Stabilization of Quadrotor Using Adaptive Fuzzy Proportional Integral Derivative Controller

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ABSTRACT

Quadrotor is an unmanned aerial robot from multi-rotor drones group that has high maneuverability, vertical take-off and landing and stationary flight capabilities. In the most practical applications, quadrotor system is subjected to external disturbance forces due to wind and unbalanced weight or inertia of the payload. In order to maintain balance and hold the position, attitude stabilization of quadrotor is necessary in the presence of disturbances and unbalanced forces. Using conventional controllers with constant gains is not very efficient to eliminate variable disturbances that affect quadrotor motion in different conditions. In this paper, an adaptive fuzzy proportional integral derivative controller is designed for quadrotor attitude stabilization in which controller gains are regulated continuously based on the adaptive laws and the fuzzy inference system. The performance of the proposed controller is examined in disturbance rejection test and is compared to conventional proportional integral derivative controller. Also, performance of the proposed controller is approved by hardware in the loop experimental tests using a 3 degree of freedom pilot platform. The experimental results will show the effectiveness on the adaptive fuzzy proportional integral derivative controller compared with the conventional proportional integral derivative controller.

KEYWORDS

Quadrotor, Attitude control, Adaptive fuzzy, Hardware in loop, External disturbance.

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1. Introduction

In recent decades, the stability analysis and control design of various kinds of unmanned aerial vehicles (UAVs) have received much attention. The UAVs are widely used in several tasks such as visual acquisition, surveillance, exploration and disaster assistance in urban circumstances [1]. Consequently, it is studied for different kinds of UAVs such as fixed-wing airplanes, helicopters and also quadrotors. Quadrotor is the most popular kind of multi-rotor UAVs due to its simple mechanics, high maneuverability and performing stable stationary flight.

The motion control of a quadrotor is a challenging problem due to its nonlinear under-actuated dynamics. Specially, controlling lateral motion of a quadrotor is the main problem since it is associated with under-actuated sub-system of the quadrotor dynamics. Several approaches are presented to control design and stability analysis of quadrotors and some strategies have been developed to solve the path following problems [2, 3].

The model-based methods presented to control design of quadrotors involve two major drawbacks. They need fast and heavy computation units due to their complicated and time consuming control laws. On the other hand, they are restricted for autonomous long-range applications where the imposed communication delay with stationary control unit disrupts real time operation of the quadrotor [4]. Motivated by previous studies, in this paper, the fuzzy logic is employed to design an adaptive fuzzy-PID controller for nonlinear under-actuated dynamics of the quadrotor. To achieve a robust performance against external disturbances, all PID gains are updated individually. Moreover, a compensator is added to control structure to weaken the estimation errors of the adaptive fuzzy-PID controller. Performance of the proposed adaptive fuzzy-PID controller is compared with conventional PID controller which shows significant improvement in tracking accuracy.

2. Dynamic modeling and control design

The Quadrotor has a simple mechanical structure consisting of a symmetric cross-shaped rigid body and four electrical rotors which are located at the end of cross arms. Schematic model of a quadrotor is depicted in Fig. 1. The trust force (T) and the aerodynamic moment (Q) are calculated as follows [5]

$$T = b\omega^2, \qquad Q = d\omega^2 \tag{1}$$

where b and d are constant positive values and ω is the angular velocity. The translational dynamics of a quadrotor is given form Newton approach [5]

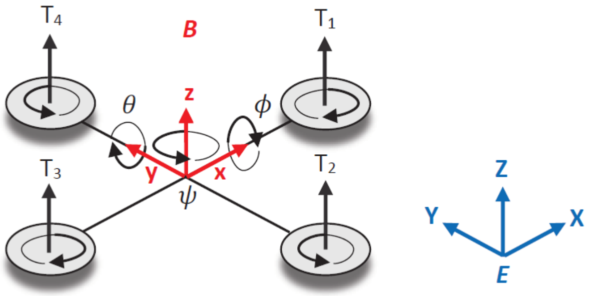

Figure 1. Schematic model of a quadrotor

$$\begin{pmatrix} \ddot{X} \\ \ddot{Y} \\ \ddot{Z} \end{pmatrix} = \begin{pmatrix} U_1\left(c_\phi s_\theta c_\psi + s_\phi s_\psi\right)/m \\ U_1\left(c_\phi s_\theta s_\psi - s_\phi c_\psi\right)/m \\ U_1 c_\phi c_\theta / m - g \end{pmatrix} \tag{2}$$

The rotational dynamics is presented as follows [5]

$$\begin{pmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{pmatrix} = \begin{pmatrix} \dfrac{U_2 - J_r\dot{\theta}\omega_r + (I_{yy} - I_{zz})\dot{\psi}\dot{\theta}}{I_{xx}} \\ \dfrac{U_3 + J_r\dot{\phi}\omega_r + (I_{zz} - I_{xx})\dot{\psi}\dot{\phi}}{I_{xx}} \\ \dfrac{U_4 + (I_{xx} - I_{yy})\dot{\theta}\dot{\phi}}{I_{zz}} \end{pmatrix} \tag{3}$$

The quadrotor is an under-actuated system because it has six degrees of freedom but only four actual inputs. As a result, only four DOFs can be controlled independently. Eq. (3) can be represented as follows

$$\begin{pmatrix} \ddot{\phi} \\ \ddot{\theta} \\ \ddot{\psi} \end{pmatrix} = \begin{pmatrix} \dfrac{-J_r\dot{\theta}\omega_r + (I_{yy} - I_{zz})\dot{\psi}\dot{\theta}}{I_{xx}} \\ \dfrac{J_r\dot{\phi}\omega_r + (I_{zz} - I_{xx})\dot{\psi}\dot{\phi}}{I_{xx}} \\ \dfrac{(I_{xx} - I_{yy})\dot{\theta}\dot{\phi}}{I_{zz}} \end{pmatrix} + \begin{pmatrix} \dfrac{1}{I_{xx}} & 0 & 0 \\ 0 & \dfrac{1}{I_{yy}} & 0 \\ 0 & 0 & \dfrac{1}{I_{zz}} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ U_3 \end{pmatrix} + \begin{pmatrix} d_\phi \\ d_\theta \\ d_\psi \end{pmatrix} = \mathbf{F} + \mathbf{GU} + \mathbf{D} \tag{4}$$

The following feedback linearization controller is introduced to yield three independent dynamical equations

$$\mathbf{U} = -\mathbf{F}/\mathbf{G} + \boldsymbol{\tau} \tag{5}$$

For each of the resultant second-order equations, a same control procedure is designed. These equations are in the following form

$$\ddot{x} = f(x,\dot{x}) + g(x,\dot{x})u + d, \qquad y = x \tag{6}$$

where $f(.)$ and $g(.)$ are nonlinear bounded functions. By defining the tracking error as $\mathbf{e} = y - y_r$, we will have

$$\begin{aligned} &\ddot{\mathbf{e}} + \mathbf{k}^T\mathbf{e} = g(\mathbf{x})(u - u^*) + \mathbf{d}, \\ &u^* = \frac{-1}{g(\mathbf{x})}\left(f(\mathbf{x}) - \ddot{y}_r + \mathbf{k}^T\mathbf{e}\right) \end{aligned} \tag{7}$$

For above system, an adaptive fuzzy-PID controller is designed as $\boldsymbol{\tau} = \boldsymbol{\tau}_{PID} + \upsilon$. The term υ is a H_∞ compensator defined by $\upsilon = -\mathbf{B}^T\mathbf{Pe}/\lambda$ where λ is a positive value and $\mathbf{P}$ is a positive definite matrix calculated by the following equation

$$\mathbf{A}T\mathbf{P} + \mathbf{PA} + \mathbf{Q} - \frac{2}{\lambda}\mathbf{PBB}^T\mathbf{P} + \frac{1}{\rho^2}\mathbf{PBB}^T\mathbf{P} = \mathbf{0}, \quad 2\rho^2 \geq \lambda \tag{8}$$

The control input $\boldsymbol{\tau}_{PID}(\xi \mid \theta) = \boldsymbol{\theta}^T\boldsymbol{\xi}(\mathbf{e})$ is defined where $\boldsymbol{\theta} = \left[K_P, K_I, K_D\right]$, $\boldsymbol{\xi}(\mathbf{e}) = [\mathbf{e}, \mathbf{e}_I, \mathbf{e}_D]^T$, $\mathbf{e}_I = \int \mathbf{e}(t)dt$ and $\mathbf{e}_D = \dot{\mathbf{e}}(t)$. All gains K_P, K_I and K_D are estimated by a Zero-order Takagi-Sugeno fuzzy system.

3. Experimental Study

To validate the proposed approach, a 3DOF experimental setup is investigated as shown in Fig. 2.

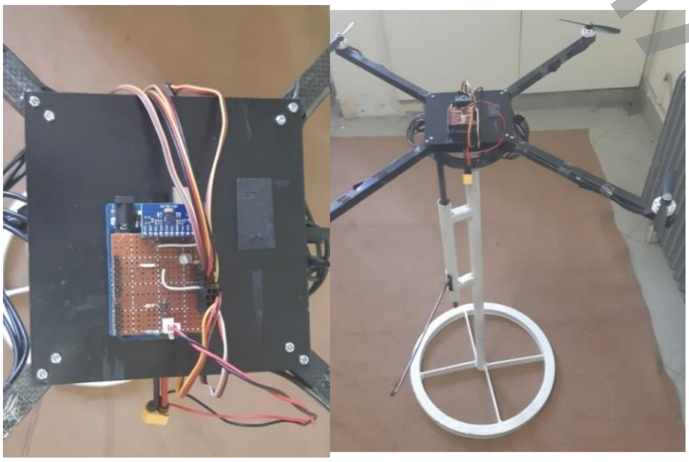

Figure 2. Experimental setup

Fig. 3 depicts the stabilization performance of roll, pitch and yaw angles in presence of external disturbance. As this figure illustrates, the proposed adaptive fuzzy-PID controller has significantly better performance compared with the conventional PID controller.

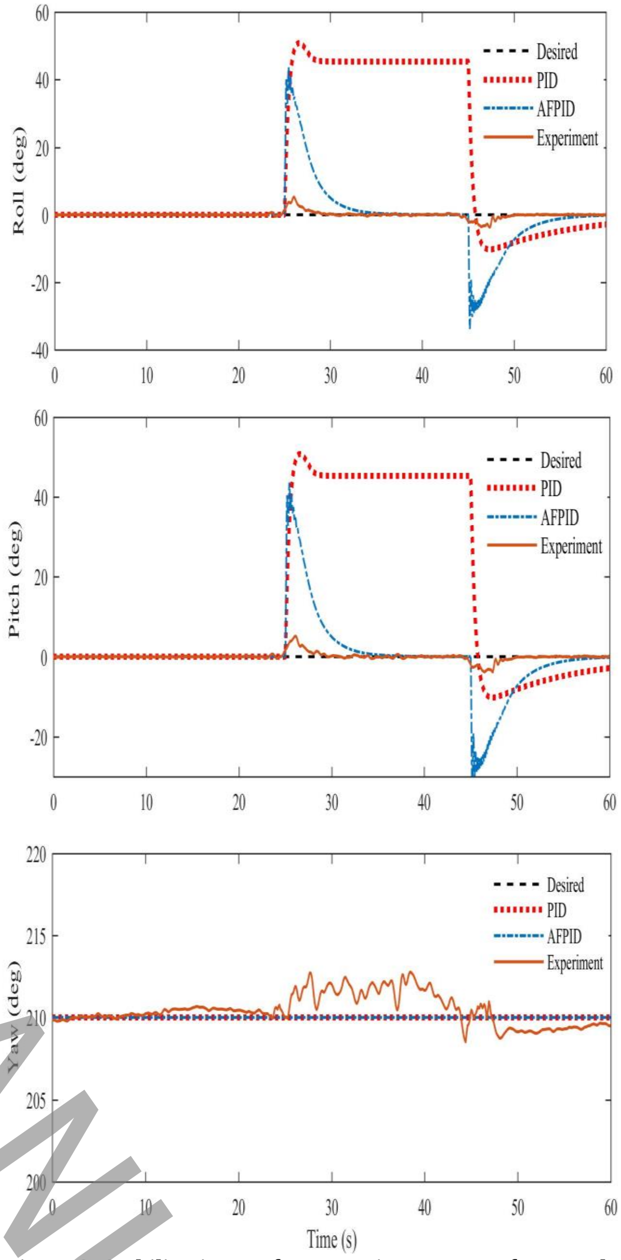

Figure 3. Stabilization performance in presence of external disturbance

4. Conclusion

In this paper, the angular stabilization problem of quadrotors was studied. An adaptive fuzzy-PID controller was presented to assure the asymptotic tracking of yaw, roll and pitch angles in presence of nonlinear uncertain dynamics and external disturbance. Compared with the previous studies, in this paper, all PID control gains were updated individually which provided a better performance in tracking the desired signals. Experimental results were provided to show the effectiveness of the proposed approach.

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