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Research article

Flocking of quad-rotor UAVs with fuzzy control

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ABSTRACT

This paper investigates the flocking problem of quad-rotor UAVs. Considering the actual situations, we derived a new simplified quad-rotor UAV model which is more reasonable. Based on the model, the T-S fuzzy model of attitude dynamic equation and the corresponding T-S fuzzy feedback controller are discussed. By introducing a double-loop control construction, we adjust its attitude to realize the position control. Then a flocking algorithm is proposed to achieve the flocking of the quad-rotor UAVs. Compared with the flocking algorithm of the mass point model, we dealt with the collision problem of the quad-rotor UAVs. In order to improve the airspace utilization, a more compact configuration called quasi e-lattice is constructed to guarantee the compact flight of the quad-rotor UAVs. Finally, numerical simulations are provided to illustrate the effectiveness of the obtained theoretical results.

1. Introduction

With the rapid development of the microprocessor and the inertial sensor, Unmanned Aerial Vehicles (UAVs) have been widely applied in many areas of military and civilian with popular applications, such as monitoring of traffic conditions, recognition and surveillance of vehicles, search and rescue operations, and aerial photography for real estate evaluations.

Although the quad-rotor UAV has many applications, it is a challenging issue to design a stable flight controller. The main approaches to derive the model are Euler-Lagrange approach and Newton-Euler approach [1,2]. The complete dynamical model of quad-rotor is very complex, because it is an under-actuated and highly-coupled nonlinear system. For this reason, the existing works usually design attitude controller with a simplified attitude model which assumes the pitch angle θ and roll angle ϕ are very small [3,4]. With this assumption, the Euler angle angular velocity $\dot{\boldsymbol{\eta}}$ is equal with the angular velocity of the fuselage expressed in the body-fixed frame. There is no doubt that the assumption is reasonable when the quad-rotor UAV keeps hovering in the air. But it is inflexible when these two angles are quite small at the same time. Otherwise, the simplified attitude model has a relatively large difference to the actual model.

Researches have proposed kinds of control strategies to stabilize the quad-rotor attitude system. The nonlinear dynamic inversion (NDI) attitude controller is a model-based controller which requires modeling all of the vehicle forces and dynamics [5]. So it is very sensitive to dynamic model of the real vehicle. Incremental nonlinear dynamic inversion (INDI) is a sensor-based control approach which does not require an accurate model of the vehicle [6]. The two main challenges of the INDI controller are the delay in the angular acceleration measurement and online estimating the control effectiveness. $\mathcal{L}_1$ adaptive attitude controller is designed for solving the problem of model uncertainty and environmental disturbance [7]. It enables fast adaptation with guaranteed robustness. In order to ensure the performance, these controllers need obtain the actual actor feedback signals. While it is very difficult in the real life. That is why so many open source quad-rotor projects and commercial products are focusing on the PID controller [8], even though PID control method only applies to an uncoupled system.

In this paper, we derived out a more reasonable simplified attitude model by just assuming the roll angle $\phi \approx 0$. Under the condition of zero roll angle, we can control the position of the quad-rotor UAV by tuning yaw angle and pitch angle. In addition, flight control algorithm can guarantee quad-rotor UAV stable and flexible flight by adjusting the yaw angle and pitch angle. That is, we can guarantee the assumption reasonable even when we need it to quickly move to a specific position. Furthermore, the simplified system is also nonlinear. The T-S fuzzy model can be a universal function approxima-

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tor, which is able to approximate any smooth nonlinear functions to any degree of accuracy [9]. T-S fuzzy model has been employed to approximate nonlinear dynamic systems to efficiently solve the nonlinear control problem. Fuzzy state feedback controller which satisfies control performance specifications such as constraints on control input and out, decay rate, and disturbance rejection can be designed with PDC and LMI technology [10]. The fuzzy controller is very easy to be used in the real life for its simple structure, less computational complexity and high control performance. In this paper, we derived a more reasonable simplified attitude model and designed a T-S fuzzy attitude controller of it.

For the limited ability of a single vehicle, some complex tasks cannot be accomplished by just one quad-rotor UAV. In real-life situation, many missions want quad-rotor UAVs to cooperate with each others [11]. Just like flocking behavior of animals, which can increase the chance of finding food, avoiding predators, saving energy, etc. Early researches about flocking behavior are mainly focus on agents of the point mass model. Researchers studied in biophysics and computer graphics did an amount of work in modeling and simulating multi-agent systems [12,13]. Then, flocking controllers using different strategies are proposed, such as leader-follower strategy [14,15], virtual leader strategy [16,17], Lyapunov-based control strategy [18]. Recently, with the development of flocking technology, there are many achievements in formation control, cooperative control and flocking control for agents of real vehicles. Jonathan R.T. Lawton proposed a decentralized approach to formate mobile robots [19]. K.D. Do studied coordination control for a group of under-actuated omnidirectional intelligent navigators [20]. Real-time flocking of multiple-quadrotor system in 2-D space was discussed in Ref. [21].

Unlike the flocking algorithm of the mass point model, we should consider the size of the actual object and the different requirement in safe distance of it. The new no collision condition is the center distance of the adjacent objects should be more than their diameter. Therefore, the flocking controller should keep the distance of any two quad-rotor UAVs is not less than their diameter. Besides, most of the flocking algorithms construct a configuration which the distance between any two adjacent agents are equal (e.g. α-lattice in Ref. [16]), and this configuration is suitable for the point mass type. However, the requirement of safe distance in different directions is usually different in fact. For the quad-rotor UAV, airflow generated by the propeller will affect on other quad-rotor UAVs in the vertical direction. In addition, the position accuracy in the vertical direction and horizontal direction is always different. In this situation, if we also want to build a α-lattice, the safe distance must be the largest one among all the directions. Then, the configuration constructed with a spherical artificial potential field is relatively loose. We introduced an ellipsoidal artificial potential field function in the flocking algorithm to construct a more compact configuration called e-lattice. E-lattice makes quad-rotor UAVs using less space when they perform flocking, and then it will improve the airspace utilization.

The paper is organized as follows: Section 2 presents the complete and simplified dynamical model of the quad-rotor. A T-S fuzzy state feedback controller is solved out with LMI technology in Section 3. In Section 4, we introduce some preliminaries for the flocking algorithm. A flocking algorithm which improves the airspace utilization is proposed in Section 5. Simulation results are presented in Section 6. Finally, in Section 7, some conclusions are given.

2. Quad-rotor dynamic model

A quad-rotor has four rotors, in which the front and rear rotors rotate in a counter-clockwise direction while the left and right rotors rotate in a clockwise direction. We assume the quad-rotor is rigid body and can obtain the complete dynamical equation with knowledge of the rigid body mechanics.

The complete dynamical model can be obtained by using Euler-Lagrange approach [2]. The positional system and attitude system's equations are

$$\begin{cases} m\ddot{x} = u(\cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi) \\ m\ddot{y} = u(\sin\psi\sin\theta\cos\phi - \cos\psi\sin\phi) \\ m\ddot{z} = u\cos\theta\cos\phi - mg \end{cases} \tag{1}$$

$$\begin{aligned}\ddot{\boldsymbol{\eta}} &= \mathbb{J}^{-1}\left(\boldsymbol{\tau} - \left(\dot{\mathbb{J}} - \frac{1}{2}\frac{\partial(\dot{\boldsymbol{\eta}}^T\mathbb{J})}{\partial\boldsymbol{\eta}}\right)\dot{\boldsymbol{\eta}}\right) \\ &= \mathbb{J}^{-1}\left(\boldsymbol{\tau} - C(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})\dot{\boldsymbol{\eta}}\right),\end{aligned} \tag{2}$$

where $\boldsymbol{\eta} = (\psi, \theta, \phi)^T$ is the attitude angle vector, u is the total thrust, m is the quad-rotor's mass, g is the gravitational acceleration, $C(\boldsymbol{\eta}, \dot{\boldsymbol{\eta}})$ is the Coriolis term, $\mathbb{J}^{-1}$ is the inverse of matrix $\mathbb{J} = W_\eta^T \boldsymbol{I} W_\eta$, $\boldsymbol{I} = diag(I_x, I_y, I_z)$ is the inertia matrix of quad-rotor UAV,

$$W_\eta = \begin{bmatrix} -\sin\theta & 0 & 1 \\ \cos\theta\sin\phi & \cos\phi & 0 \\ \cos\theta\cos\phi & -\sin\phi & 0 \end{bmatrix}.$$

With two assumptions below, a reasonable simplified dynamic model is derived out.

Assumption 1. *Quad-rotor is strictly symmetric, whose inertia matrix is approximate to* $diag(I_m, I_m, 2I_m)$.

Assumption 2. *The roll angle is very small in the process of the flight. So,* $\sin\phi = 0, \cos\phi = 1$.

Remark 1. The use process of the quad-rotor UAV can usually be divided into four phases: takeoff, move, hover and land. It always maintains level in the phase of taking off, landing and hovering, then the Assumption 2 is correct. The quad-rotor UAV changes its position by adjusting its attitude angles. Traditional simplified model assumes the roll angle and pitch angle are very small. These two angles should not be too large at the moving phase, it will limit its mobility. In this paper, we can adjust its yaw angle and pitch angle to guarantee its maneuverability and keep its roll angle $\phi = 0$ to guarantee the rationality of Assumption 2.

Considering the Assumption 2, the positional system is simplified to

$$\begin{cases} \ddot{x} = u/m \cdot \cos\psi\sin\theta \\ \ddot{y} = u/m \cdot \sin\psi\sin\theta \\ \ddot{z} = u/m \cdot \cos\theta - g \end{cases}. \tag{3}$$

For the attitude system, we have

$$\begin{aligned} B^* &= \mathbb{J}^{-1}|_{\boldsymbol{I}=diag(I_m,I_m,2I_m),\phi=0} \\ &= \frac{1}{2I_m}\begin{bmatrix} \sec^2\theta & 0 & \tan\theta\sec\theta \\ * & 2 & 0 \\ * & * & 1+\sec^2\theta \end{bmatrix}, \end{aligned}$$

$$C_1(\boldsymbol{\eta},\dot{\boldsymbol{\eta}}) = C(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})|_{\boldsymbol{I}=diag(I_m,I_m,2I_m)}.$$

Then,

$$\begin{aligned} \zeta &= -B^* \cdot C_1(\boldsymbol{\eta},\dot{\boldsymbol{\eta}})|_{\phi=0} \cdot \dot{\boldsymbol{\eta}} \\ &= \begin{bmatrix} \dot{\theta}\sec\theta\sin\theta & 0 & \dot{\theta}\sec\theta \\ -\dot{\psi}\cos\theta\sin\theta & 0 & 0 \\ \dot{\theta}\sec\theta & -\dot{\psi}\cos\theta & \dot{\theta}\sec\theta\sin\theta \end{bmatrix}\begin{bmatrix}\dot{\psi} \\ \dot{\theta} \\ \dot{\phi}\end{bmatrix} \\ &= A^*\dot{\boldsymbol{\eta}}. \end{aligned} \tag{4}$$

Finally, the simplified attitude system can be expressed as

$$\ddot{\boldsymbol{\eta}} = A^*\dot{\boldsymbol{\eta}} + B^*\boldsymbol{\tau}. \tag{5}$$

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