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High-performance trajectory tracking control of a quadrotor with disturbance observer

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ABSTRACT

In this paper, a flight controller with disturbance observer (DOB) is proposed for high-performance trajectory tracking of a quadrotor. The dynamic model of the quadrotor, considering the external disturbances, model mismatches and input delays, is firstly developed. Subsequently, a DOB-based control strategy is designed with the backstepping (BS) technique. In this control scheme, the DOB serves as a compensator, which can effectively reject model mismatches and external disturbances. In this case, the trajectory tracking controller is designed according to the nominal model. Then, the input-to-state stability (ISS) analyses of the developed controllers are presented, which theoretically guarantees the robustness of the developed controller. Finally, comparative studies are carried out. Three types of disturbances including payloads, rotor failures and wind are chosen to verify the effectiveness of the development. The results from simulations and experiments show that the proposed controller provides better performances than the traditional nonlinear controllers.

1. Introduction

Over the recent years, the quadrotors, a kind of unmanned aerial vehicles (UAV), attract more and more attentions in the robotics community [1]. With their small size and agile maneuverability, the quadrotors provide mobilities which cannot be covered by humans, for instance, in cluttered or dangerous environments where the human being is at risk [2,3]. These capabilities of quadrotors allow to cope with a diverse scenarios imposed by real-world missions [4], such as photography, traffic monitoring, reconnaissance, homeland security, damage assessment, etc. [5].

In these missions, the performance of the quadrotors implicitly depends on the flight controllers. Therefore, high-performance controllers are essential and many researchers have involved themselves into this field. Bouabdallah et al. firstly developed a group of classical controllers, including the proportional-integral-derivative (PID) controller, linear quadratic (LQ) controller [6], backstepping controller and sliding-mode controller [7]. These controllers solve the basic problems of flight control and some of them are still widely adopted nowadays [8,1]. Later, for the purpose of robust control, modern control theories were implemented in the controller design, such as Lyapunov function design method [9] and hierarchy theory [10]. The effectiveness of these controllers were verified theoretically and experimentally. However, no evidence shows these controllers can handle external disturbances and model mismatches, such as payloads, wind and rotor damages. This drawback obviously deteriorates the performance of the flight controllers. Therefore, more reliable and robust controllers are necessary. To this end, several groups have made efforts to develop controllers that are capable of disturbance rejection. A representative development is a so called composite model reference adaptive controller developed by Dydek et al. [11]. This controller was verified to be capable of dealing with rotor failures in an experiment of altitude control. In [4,12–14], adaptive controllers of different structures were also verified by simulations and experiments on ground stations. Alternatively, the DOB-based controller is robust to external disturbances and model mismatches without the use of high control gain or extensive computational power [15]. The DOB provides a feasible approach to estimate disturbances while relying only on knowledge of the nominal model and limits of the disturbances [15,16].With the introduction of DOB, the controller can then be developed based on traditional methods. Comparing to the adaptive control, the DOB makes the controller design more flexible and reduces the complexities [17]. Besnard et al. firstly adopted sliding mode disturbance observer for robust controller design [15,18,19]. Later, different kinds of DOB-based controllers

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were developed for disturbance rejection in attitude control and 2D trajectory tracking [20–23].

Results from these works show the potential capabilities of DOB-based controllers for handling external disturbances and model mismatches, such as wind and actuator failure [15]. However, none of them is developed for the purpose of trajectory tracking of a quadrotor in real time. Therefore, this work is motivated to develop a high-performance DOB-based controller with experimental studies. Firstly, in order to develop an effective model for the controller design, the dynamic behaviors of the quadrotor are further studied by considering external disturbances, model mismatches and input delays. Subsequently, the DOB is designed and an integral filter is introduced to alleviate the effects of input delays and high frequency noises. In this way, the filter's output can be viewed as the estimate of the lumped disturbance. By subtracting this estimate, the major disturbances, especially low-frequency disturbances, can be eliminated. In such a case, a control scheme for trajectory tracking can be developed according to the nominal model. In this control scheme, the position error is stabilized by a proportional-integral (PI) controller, and the velocity error is stabilized by a BS controller. The stability analysis is then provided to theoretically confirm the robustness of the developed controllers. Finally, experiments are carried out to verify the development.

The contribution of this paper lies in two aspects. Firstly, to get a better understanding of the quadrotor's dynamic behavior, a mathematical model, which considering the external disturbances, model mismatches and input delays, is developed. Secondly, a high-performance DOB-based backstepping controller is developed and experimentally verified for the real-time trajectory tracking of the quadrotor. This controller can cope with wind, varying payloads and rotor failures. To the best knowledge of the authors, no such controller has been adopted in the real time trajectory tracking of a quadrotor.

The remainder of this paper is organized as follows. Section 2 proposes the dynamic model of the quadrotor. The DOB-based controller is designed in Section 3, and the stability analysis is provided in Section 4. Then the results from simulation and experiments are shown in Section 5, and Section 6 concludes this work.

2. Quadrotor model and problem statement

To facilitate the controller design, the dynamic model of the quadrotor is developed in this section. In this model, external disturbances, input delays and model mismatches are considered as the lumped disturbance which will be handled by the following developed controller.

2.1. Quadrotor dynamics

As shown in Fig. 1, the quadrotor is actuated by four rotors on the endpoints of an X-shaped frame. The collective thrust of these four rotors accelerates the quadrotor along its normal direction (Z_B). In order to balance the yawing torque, rotors attached on the Y_B axis rotate in clockwise direction, and the rotors attached on the X_B axis rotate in counterclockwise direction. As a result, the difference of collective torques between these two axes produces a yawing torque. Similarly, differences of thrusts between rotors on the X_B axis and Y_B axis produce a pitching torque and a rolling torque respectively. Therefore, four control inputs can be defined as

$$\begin{cases} U_1 = F_1 + F_2 + F_3 + F_4 \\ U_2 = (F_4 - F_2)L \\ U_3 = (F_3 - F_1)L \\ U_4 = M_1 - M_2 + M_3 - M_4 \end{cases} \tag{1}$$

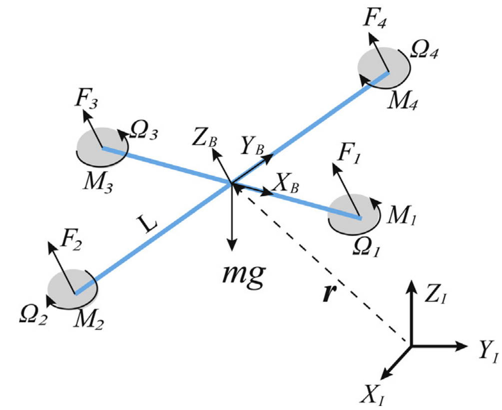

Fig. 1. A depict for the quadrotor. $X_I - Y_I - Z_I$ is the inertial coordinates and $X_B - Y_B - Z_B$ is the body fixed coordinates.

where L is the length from the rotor to the center of the mass of the quadrotor, F_i is the generated thrust, and M_i is the generated torque.

The thrusts and torques can be obtained by varying the rotary speeds of the rotors. This relations are commonly estimated by [24,25,1]

$$F_i = k_F \frac{\omega_F}{s + \omega_F} \Omega_{id}, \quad M_i = k_M \frac{\omega_M}{s + \omega_M} \Omega_{id} \tag{2}$$

where k_F, k_M, ω_F, ω_M are constants related to the rotor, and Ω_{id} is the reference for the speed of the rotor.

In view of (1) and (2), the rigid body dynamics using Newton–Euler formalism is governed

$$\begin{cases} m\ddot{\boldsymbol{r}} = U_1 \boldsymbol{Z}_B - mg\boldsymbol{Z}_I - \boldsymbol{k} \circ \dot{\boldsymbol{r}} \circ |\dot{\boldsymbol{r}}| \\ \boldsymbol{I}\ddot{\boldsymbol{q}} = \begin{bmatrix} U_2 & U_3 & U_4 \end{bmatrix}^T - \dot{\boldsymbol{q}} \times \boldsymbol{I}\dot{\boldsymbol{q}} \end{cases} \tag{3}$$

where m is mass of the quadrotor, g is the local gravity constant, $\boldsymbol{r}$ is the position in inertia frame with $\boldsymbol{r} = [x, y, z]^T$, $\boldsymbol{q}$ is the attitude in body frame with $\boldsymbol{q} = [\phi, \theta, \psi]^T$, $\boldsymbol{I}$ is the rotary inertia, $\boldsymbol{k}$ is a constant to estimate the aerial drag effects, and the symbol $\circ$ denotes the element-wise product.

Since the rotary inertia is small and the quadrotor is symmetric, the term $\dot{\boldsymbol{q}} \times \boldsymbol{I}\dot{\boldsymbol{q}}$ is small and insignificant [1,26,7,11,27]. Therefore, (3) can be reduced into

$$\begin{cases} \ddot{x} = \dfrac{1}{m}(U_1(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) - k_x \dot{x}|\dot{x}|) \\ \ddot{y} = \dfrac{1}{m}(U_1(\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi) - k_y \dot{y}|\dot{y}|) \\ \ddot{z} = \dfrac{1}{m}(U_1(\cos\phi \cos\theta) - k_z \dot{z}|\dot{z}| - mg) \\ \ddot{\phi} = \dfrac{U_2}{I_{xx}} \\ \ddot{\theta} = \dfrac{U_3}{I_{yy}} \\ \ddot{\psi} = \dfrac{U_4}{I_{zz}} \end{cases} \tag{4}$$

where I_{xx}, I_{yy}, and I_{zz} are the rotary inertia of the quadrotor respect to the X_B, Y_B, and Z_B axis.

2.2. Problem statement

Traditional controllers, such as PID controller, LQ controller [6] and sliding-mode controller [7], for trajectory tracking are commonly developed based on (4) [1,24,25]. However, as uncertainties may arise in (4), these controllers inherently lack of the capabilities