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A high-performance flight control approach for quadrotors using a modified active disturbance rejection technique

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ABSTRACT

In practice, the parameters of the flight controller of the quadrotors are commonly tuned experimentally with respect to a certain type of reference, such as the step reference and the unit-ramp reference. In this way, the performance of the flight controller might be affected by the variations of the references in real-time flights. Besides, real-time dynamic effects such as measure noises, external disturbances and input delays, which are usually neglected in the reported works, could easily deteriorate the performances of the flight controllers. This work is thereby motivated to develop a high-performance flight control approach utilizing a modified disturbance rejection technique for the quadrotors suffering from input delays and external disturbances. This control approach is developed in a cascaded structure and the attitude angles are chosen as the pseudo control inputs of the translational flight of the quadrotors. To facilitate the development, the dynamic model of the quadrotors is firstly formulated by including the effects of input delays, and the dynamics of the pseudo control variables are identified through real-time experiments. Based on the identified model, the flight control approach is proposed with a modified active disturbance rejection technique, which consists of a time optimal tracking differentiator, an extended state observer/predictor, and a nonlinear proportional–derivative controller. The tracking differentiator is designed to generate smooth transient profiles for the references, and the extended state observer/predictor is implemented for lumped disturbance estimation and state estimation considering the input delays. With the aid of the tracking differentiator and the extended state observer/predictor, the nonlinear proportional–derivative controller can thereby establish a fast tracking control and effectively reject the estimated disturbances. To verify the feasibilities of this development, comparative tests are carried out in both simulations and experiments. The results show that in the presence of small lumped disturbances, such as the measurement zero-drift, the steady-state errors of the proposed control approach for the ramp responses are less than 2 cm, and in the tests of sinusoidal trajectory tracking, the cross-tracking errors are less than 0.04 m. When with large disturbance airflow that is equivalent to strong breeze, the steady-state error achieved by the proposed flight controller is also less than 10 cm. All of these facts demonstrate the effectiveness of this development.

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1. Introduction

In the last decade, numbers of amazing developments of the quadrotors have been presented in the robotics community [1–6]. In view of their excellent performances in the experimental demonstrations, these kinds of unmanned aerial vehicles are hopeful to be adopted for various real-time applications in civil market, such as search, photography and automatic delivery [7,4].

Successful implementation of these applications is closely tied to the performance of the flight controllers [8]. Therefore, numbers of researchers have devoted themselves to develop high performance flight control strategies for the quadrotors in the last few years. Owing to their efforts, a lot of novel controllers such as linear quadratic (LQ) controller [9], backstepping controller, sliding-mode controller [10], and linear matrix inequalities (LMI) based controller [11] have been developed. Unfortunately, most of these controllers are not widely adopted by real-time applications nowadays, and the dominant flight controller of the quadrotors

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is still the classical proportional–integral–derivative (PID) controller [7,12]. These are because the PID controller can be straightforwardly implemented by the practitioners, and the PID controller itself is computationally efficient for the concurrent processing capabilities of the on-board micro control units (MCUs). However, regardless of these superiorities, the PID controller might be not able to well cope with many real-time issues such as communication delays, changing dynamics, and external disturbances [4]. In addition, at least three problems may arise when only conventional PID is adopted for the flight control. Firstly, the integral term of PID controller introduces extra phase lag, which could reduce the stability margin and lead to oscillations when changing disturbances exist. Secondly, as high frequency noises exist in the measurement, the derivative term may not be implementable. Thirdly, as the references of way-point navigations are often constructed with step functions, they are not consistent with the dynamics of the system and the control inputs are required to make sudden jumps for fast tracking of these references [13].

To enhance the performance of the PID controller, several researchers have begun to investigate advanced PID control techniques. Owing to their efforts, some novel controllers, such as fractional order PID (FOPID) controllers [14–16], disturbance observer (DOB) based controllers [17,18] and active disturbance rejection controllers (ADRC) [19,20], have been developed. Among these controllers, the ADRC is the most promising candidate that can well handle the aforementioned drawbacks of the PID controllers. The ADRC consists of three subsystems: a nonlinear PD controller, a tracking differentiator (TD) and an extended state observer (ESO). The TD can smooth the reference by establishing a transient profile, and the ESO can effectively eliminate the measurement noises and estimate the lumped disturbance. With the smoothed reference and the estimated disturbance, the nonlinear PID controller can then establish a fast tracking control. With these functionalities, the ADRC is practically valuable for the flight control of the quadrotors. However, except for some simulation studies [19,20], there is no real-time flight controller developed based on the ADRC in view of the accumulated works. These are because the parameter tuning process as well as the structure of the classic ADRC, especially its nonlinear PD part, are not explicit enough for directly applying in the flight control of the quadrotors, and the performance of the ADRC could also be deteriorated by some real-time dynamic effects. In particular, as reported in [17], input delays caused by the phase lags of the pseudo control inputs [21] and communication delays of the teleoperation [22,23] will introduce extra difficulties for the disturbance rejection of the flight controllers.

To address such challenges, a new control approach, which is based on a modified ADRC (MADRC), is proposed in this paper to enhance the real-time performance of the translational flight control of the quadrotors suffering input delays and external disturbances, and this is conducted as follows. Firstly, the dynamic model of the quadrotors is formulated by including the effects of input delays, and the dynamics of the pseudo control variables are identified through real-time experiments. Subsequently, the flight control approach that contains three subsystems: an ESO/predictor, a TD, and a modified nonlinear PD controller is developed for high performance flight control of the quadrotors. In the ESO/predictor, the dynamics of the pseudo control variables is included for the state estimation, which is thereby possible to eliminate the effects of input delays. With well estimated states, the nonlinear PD controller is then implemented for fast tracking the time optimal reference generated by the TD. Besides, as the nonlinear PD controller is modified into a cascaded structure with less parameters, it is more straightforward for practitioners and less experimental trials are required for parameter tuning. Finally, the superiorities of the proposed control approach over the classic control techniques are demonstrated through comparative tests in both simulations and experiments with a conventional proportional–proportional (P–P) controller and a DOB based proportional–proportional (DOB-P–P) controllers.

The distinctive features of this paper are as follows. Firstly, a high performance flight control approach with the MADRC is proposed, and the parameters tuning rules are also addressed in detail. This control approach can be conveniently implemented in real-time applications, and is robust to the lumped disturbances, input delays and reference variations. Secondly, the improved ESO/predictor provides a computationally efficient approach for state estimation and prediction, and the modified nonlinear PD controller is straightforward for practitioners to apply in real time applications. Finally, real-time experiments are conducted on a quadrotor suffering from measurement zero-drift and external wind gust. In this way, the feasibilities and capabilities of the proposed control approach in real-time applications are extensively studied.

The remaining part of this paper is organized as follows. In Section 2, the quadrotor model is formulated and identified, then Section 3 develops the controller based on the formulated model. Numerical Simulations are thereafter presented in Section 4, and real-time experiments are carried out in Section 5. Section 6 finally concludes this work.

2. Dynamic model

To facilitate the controller design, the dynamic model of the quadrotors is firstly formulated in this section. Based on this model, the pseudo control variables for the translational flight control are then determined, and their dynamics are identified according to real-time experiments.

2.1. Rigid body dynamics

The coordinates and free body diagram of the quadrotors are shown in Fig. 1. According to this diagram, four control inputs can be defined as

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

where L is the length from the rotor to the center of the mass of the quadrotor, and F_i and M_i are the thrust and torque generated by rotor i ($i \in \{1, 2, 3, 4\}$).

In view of Eq. (1), equations governing dynamics of the quadrotor with respect to the inertial coordinates are generally expressed as [21,24]

$$\begin{cases} \ddot{x} = \dfrac{U_1}{m}(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) \\ \ddot{y} = \dfrac{U_1}{m}(\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi) \\ \ddot{z} = \dfrac{U_1}{m}\cos\phi \cos\theta - g \\ \ddot{\phi} = \dfrac{U_2}{I_{xx}} + \dot{\theta}\dot{\psi}\left(\dfrac{I_{yy} - I_{zz}}{I_{xx}}\right) - \dfrac{J_R}{I_{xx}}\dot{\theta}\Omega_R \\ \ddot{\theta} = \dfrac{U_3}{I_{yy}} + \dot{\phi}\dot{\psi}\left(\dfrac{I_{zz} - I_{xx}}{I_{yy}}\right) - \dfrac{J_R}{I_{yy}}\dot{\phi}\Omega_R \\ \ddot{\psi} = \dfrac{U_4}{I_{zz}} + \dot{\phi}\dot{\theta}\left(\dfrac{I_{xx} - I_{yy}}{I_{zz}}\right) \end{cases} \tag{2}$$

where x, y, and z are the position of the center of mass in the inertial coordinates; ϕ, θ, and ψ are the attitude; m, I_{xx}, I_{yy}, and I_{zz} are the mass and moments of inertia of the quadrotor, respectively; J_R and Ω_R are the moments of inertia and angular velocity of the propeller blades; and g is the gravity constant.

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