Algebraic Time-Delay Control for Quadrotor Attitude Tracking in the Presence of External Disturbances

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***Abstract*—This paper proposes an algebraic time-delay control (ATDC) scheme for attitude tracking of quadrotor UAVs subject to high-amplitude, high-frequency external disturbances. The approach extends conventional time-delay control (TDC) by introducing an algebraic disturbance estimator derived from finite-difference calculus, achieving adjustable order of estimation accuracy without increasing controller complexity. The resulting controller ensures precise compensation of unmodeled dynamics and external disturbances within a simple linear structure, requiring no explicit system model. Comparative simulations with standard TDC and active disturbance rejection control (ADRC) demonstrate that ATDC provides smaller tracking error, enhanced disturbance rejection, and smooth control effort. The proposed method combines computational efficiency with high robustness, offering a promising framework for real-time UAV control.**

***Index Terms*—time-delay control, disturbance rejection, attitude control, quadrotor, model-free control.**

I. Introduction

Aerial vehicles have long been of great interest to researchers from a control systems perspective. In recent years, multirotor unmanned aerial vehicles (UAVs) have found widespread use across various industrial sectors due to their unique capabilities, such as vertical takeoff and landing, as well as agile movement in three-dimensional space [1]. A quadrotor, which features four propellers, is a typical example of such multirotor UAVs and will be the focus of this study. To ensure effective quadrotor maneuverability, robust attitude control is essential. However, the quadrotor exhibits nonlinear attitude dynamics and is frequently subjected to external disturbances during flight. Due to the complexity of this control challenge, numerous attitude control strategies have been proposed by researchers [2]. The difficulty in obtaining an accurate nonlinear mathematical model of the system has led to a shift in research focus from model-based approaches to more robust control design methods.

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One of the most extensively studied robust control approaches is sliding mode control (SMC) and its various modifications. In [3], sliding mode attitude control was applied to a quadrotor with time-varying mass under external disturbances. A generic adaptive sliding mode control strategy was implemented and experimentally tested in [4] for quadrotor attitude and altitude tracking in the presence of wind gusts. Similarly, fast nonsingular terminal sliding mode control for quadrotor attitude regulation was explored in [5], featuring an enhancement that eliminates the need for prior knowledge of the disturbance upper bound. Although numerous techniques have been developed to mitigate chattering in the SMC law, a key remaining issue is that SMC design is still partially model-dependent and has limited accuracy in disturbance estimation.

In the field of UAV attitude control, machine learning algorithms have also been investigated. In [6], quadrotor attitude control and trajectory tracking were evaluated using eight different reinforcement learning algorithms. In [7], unknown attitude and external disturbance dynamics were estimated using a predictor-based neural network, and the approach was validated experimentally. Common challenges associated with AI-based control strategies include high computational cost, difficulty in parameter tuning, and limited accuracy in disturbance estimation.

Another approach to controlling nonlinear systems affected by external disturbances is the active disturbance rejection control (ADRC) method. ADRC combines a linear or nonlinear controller with an extended state observer (ESO). The ESO estimates the system states, by aggregating all model uncertainties and unknown external disturbance dynamics into a single virtual state. In [8] and [9], ADRC with nonlinear error feedback was simulated for quadrotor attitude trajectory tracking under unknown disturbances, which were estimated using the ESO. In [10], the attitude response of a quadrotor with different load distributions on the rotor arms was experimentally evaluated using a cascaded ADRC method. Although ADRC has a simple structure and is relatively easy to implement, the ESO exhibits certain limitations. In its basic form, the ESO cannot estimate high-frequency disturbances, while the generalized ESO suffers from high observer gains, which can lead to peaking phenomena in the control signal and increased sensitivity to measurement noise [11], [12].

A control paradigm capable of effectively handling nonlinear systems without requiring mathematical model of the system or external disturbance dynamics is known as model-free control (MFC), first introduced in [13]. MFC method treats unknown system and disturbance dynamics as a lumped disturbance, which is estimated using time-delayed input and output data to approximate signal derivatives. MFC and time-delay control (TDC) are frequently used interchangeably in the literature. For instance, in [14], a TDC scheme was tested for quadrotor attitude stabilization under various external disturbances. A sliding-mode TDC approach for attitude trajectory tracking was experimentally validated in [15]. In [16], the TDC method was applied to quadrotor attitude tracking under constant disturbances introduced by attaching weights to the rotor arms. In [17] and [18], TDC with nonlinear feedback control was implemented for rigid spacecraft and aerial manipulator attitude control, respectively. Similarly, in [19], an enhanced TDC was used on a 3-DOF robotic manipulator, incorporating a TDE error correction term based on a nonlinear sliding surface. To the best of the authors' knowledge, all existing TDC schemes are providing only first-order derivative estimation accuracy. Recent studies on TDC aim to reduce TDE error by incorporating nonlinear correction terms into the control law, however, this also increases the complexity of the controller.

In this paper, we present an algebraic time-delay control (ATDC) method that enables total disturbance estimation with an adjustable order of accuracy, thereby overcoming the limited first-order estimation accuracy of conventional TDC and eliminating the need for a nonlinear correction term to compensate for the TDE error. The ATDC framework consists of an algebraic disturbance estimation algorithm based on finite-difference calculus, combined with a linear controller. Due to its simple structure, ATDC is easy to implement and computationally efficient. The proposed control approach is evaluated through numerical simulations for the case of quadrotor attitude tracking under unknown external disturbances.

The rest of the paper is organized as follows. The quadrotor attitude dynamic model is presented in section II. ATDC control design is presented in section III. Simulation results are presented in section IV. Finally, concluding remarks are summarized in section V.

II. Quadrotor attitude dynamic model

Attitude dynamic model presented in this section will not be used for controller design, but it will only serve for simulation purposes to validate our control design. Multirotors are usually made of a rigid cross frame equipped with four, six or eight rotors [20].

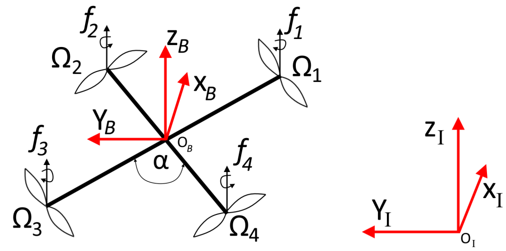

Fig. 1. Quadrotor forces in body-fixed and inertial coordinate frame.

A. Rigid body kinematics and dynamics

The rotational kinematics of a rigid body can be described by

$$\dot{\boldsymbol{\eta}} = \boldsymbol{\Omega_B}\,\boldsymbol{\omega}, \tag{1}$$

where $\boldsymbol{\eta} = [\phi\ \theta\ \psi]^\mathsf{T}$ denotes the Euler-angle vector defined using the xyz-convention, and $\boldsymbol{\omega} = [p\ q\ r]^\mathsf{T}$ represents the angular velocity vector. The matrix

$$\boldsymbol{\Omega_B} = \frac{1}{c_\theta}\begin{bmatrix} c_\theta & s_\phi s_\theta & c_\phi s_\theta \\ 0 & c_\phi c_\theta & -s_\phi c_\theta \\ 0 & s_\phi & c_\phi \end{bmatrix},$$

defines the transformation between the body-fixed and inertial coordinate frames. In this notation, $s_\eta \equiv \sin(\eta)$ and $c_\eta \equiv \cos(\eta)$.

The rotational dynamics of a rigid body about its three axes, expressed in the body-fixed reference frame, are written as

$$\mathsf{I}\,\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathsf{I}\,\boldsymbol{\omega}) = \boldsymbol{\tau} + \mathsf{d}_{\boldsymbol{\tau}}, \tag{2}$$

where $\mathsf{I} = diag\{I_x\ I_y\ I_z\}$ is the diagonal inertia matrix, $\boldsymbol{\tau} = [\tau_\phi\ \tau_\theta\ \tau_\psi]^\mathsf{T}$ is the vector of actuator generated torques, and $\mathsf{d}_{\boldsymbol{\tau}} = [d_\phi\ d_\theta\ d_\psi]^\mathsf{T}$ represents the external disturbance torque vector.

B. Quadrotor forces and moments

Quadrotors have four propellers, rotating at angular velocities Ω_i, and are producing four upward directed forces as depicted in Fig. 1.

$$f_i = k_i\,\Omega_i^2, \tag{3}$$

where $i = 1, 2, 3, 4$ and k_i denotes a positive thrust coefficient for each rotor. A control allocation approach is typically employed to convert the individual rotor forces f_i into torque components $\tau_\phi, \tau_\theta, \tau_\psi$ acting about the three mutually orthogonal body axes. These torque components are then applied as system inputs in accordance with the dynamic model given in (2).

For a quadrotor in the X-configuration, the relation between the four motor-generated thrust forces and the resulting body-axis torques is expressed through the following control allocation matrix:

$$\begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \begin{bmatrix} -r_\phi & r_\phi & r_\phi & -r_\phi \\ -r_\theta & -r_\theta & r_\theta & r_\theta \\ c & -c & c & -c \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{4}$$

where $r_\phi = l\,\sin(\alpha/2)$, $r_\theta = l\,\cos(\alpha/2)$. The parameter l denotes the distance from each motor to the center of gravity, while c represents the force-to-moment scaling coefficient.

III. Control design

In this section, first the mathematical preliminaries important for algorithm synthesis will be presented. Then, the main ideas on ATDC scheme and design of a controller using minimal model information will be introduced.

A. Preliminaries for Time-Delay Control

Here we state some fundamental finite difference calculus definitions that are used for numerical differentiation.

The difference operator $\Delta f(t) = f(t) - f(t-T)$ is related to the shift operator $\mathsf{E}f(t) = f(t-T)$ and the derivative operator $\mathsf{D}f(t) = \dot{f}(t)$ through the following expression

$$\Delta f(t) = (1-\mathsf{E})f(t) = \left(1 - e^{-T\mathsf{D}}\right) f(t), \tag{5}$$

where T is the constant time delay. From equation (5), the relationship between the derivative operator and the difference operator is obtained as

$$\mathsf{D} = -\frac{1}{T}\ln(1-\Delta). \tag{6}$$

By using the truncated power series expansion of the logarithmic function raised to the k-th power, the k-th derivative is approximated with an accuracy of order N,

$$\hat{\mathsf{D}}^k = \frac{(-1)^k k!}{T^k}\sum_{j=k}^{N}\frac{(-1)^j}{j!}s(j,k)\Delta^j, \tag{7}$$

where $s(j,k)$ are Stirling numbers of the first kind. In the last step we want to find relation between derivative and shift operator. If the power of the difference operator is expressed using the binomial formula

$$\Delta^j = (1-\mathsf{E})^j = \sum_{i=0}^{j}(-1)^i\binom{j}{i}\mathsf{E}^i, \tag{8}$$

and we insert it in (7), we get

$$\hat{\mathsf{D}}^k = \frac{1}{T^k}\sum_{i=0}^{N}\mu_{ki}\mathsf{E}^i, \tag{9}$$

where

$$\mu_{ki} = (-1)^{k+i}k!\sum_{j=\max\{i,k\}}^{N}\frac{(-1)^j}{j!}\binom{j}{i}s(j,k). \tag{10}$$

In other words, when the operator (5) is applied to the function $f(t)$, we obtain a formula for the approximation of the k-th derivative of the function

$$\mathsf{D}^k f(t) = f^{(k)}(t) \approx \hat{\mathsf{D}}^k f(t) = \frac{1}{T^k}\sum_{i=0}^{N}\mu_{ki}f(t-iT). \tag{11}$$

The larger the number of terms in the sum expansion N, the better the approximation accuracy of the derivative will be.

B. Disturbance Estimation Algorithm

We will consider a nonlinear time-varying dynamic system described by the nonlinear differential equation of order n

$$y^{(n)}(t) = f(\mathbf{x},t) + g(\mathbf{x},t)u(t), \tag{12}$$

where $\mathbf{x} = [y \;\; \dot{y} \;\; \cdots \;\; y^{(n-1)}]$ is the state vector, and $u(t)$ is the control variable. We express the dynamic system model (12) in a simpler notation

$$y^{(n)}(t) = F(t) + \alpha u(t), \tag{13}$$

where $F(t)$ is the total disturbance

$$F(t) = f(\mathbf{x},t) + (g(\mathbf{x},t) - \alpha)u. \tag{14}$$

In (14), $f(\mathbf{x},t)$ and $g(\mathbf{x},t)$ represent all internal(unknown dynamics) and external(e.g. wind gusts) disturbances. Total disturbance can be estimated by measuring position y only. Non-physical constant parameter α is meant to be chosen by the practitioner such that αu and $y^{(n)}$ are of the same magnitude. Therefore, parameter α is obtained by trials and errors, while small deviation from real value will be estimated by $F(t)$.

If (13) is rearranged and integrated m times, where $m \geq n$, we get

$$\int^{(m)} F(t)dt = \int^{(m)} y^{(n)}(t)dt - \alpha\int^{(m)} u(t)dt. \tag{15}$$

By applying approximation of the m-th derivative from (11) to the m-th integral of $F(t)$, we can obtain an estimation of the total disturbance $\hat{F}(t)$

$$\hat{\mathsf{D}}^m\int^{(m)} F(t)dt \equiv \hat{F}(t). \tag{16}$$

Equation (15) needs to be expressed in state-space form, so we introduce variables

$$x_1(t) = \int^{(m)} y^{(n)}(t)dt, \qquad z_1(t) = \int^{(m)} u(t)dt, \tag{17}$$

from which we get a representation in a state-space form

$$\begin{array}{rlcrl} \dot{z}_1 &= z_2, & & \dot{x}_1 &= x_2, \\ \dot{z}_2 &= z_3, & & \dot{x}_2 &= x_3, \\ \vdots & & & \vdots & \\ \dot{z}_m &= u(t), & & \dot{x}_{m-n} &= y(t). \end{array} \tag{18}$$

From (15),(16),(17) and by using definition for derivative approximation in (11), we obtain the formula for total disturbance estimation

$$\hat{F}(t) = \frac{1}{T^m}\sum_{i=0}^{N}\mu_{mi}[x_1(t-iT) - \alpha z_1(t-iT)], \tag{19}$$

where T is the time-delay constant parameter, and N is the already mentioned order of estimation accuracy. Parameter T should be selected in relation to the sampling period T_s, typically $T = kT_s$, where $k \in [50, 100]$, ensuring a compromise between noise sensitivity and derivative approximation accuracy. Parameter N increases estimation accuracy but also amplifies high-frequency noise, thus practical values are typically $N = m+1$ or $N = m+2$.

C. Relation to conventional TDC

For a system of order m, conventional TDC uses only m-delayed samples, which results in a numerical differentiation scheme with first-order accuracy

$$f^{(m)}(t) \approx \frac{1}{T^m} \sum_{i=0}^{m} (-1)^i \binom{m}{i} f(t - iT). \tag{20}$$

The limitation of conventional TDC arises from its first-order derivative approximation (20), which introduces significant phase lag for high-frequency components. In contrast, the ATDC estimator (19) achieves higher-order accuracy ($N \geq m$), reducing phase error and improving disturbance reconstruction at higher frequencies. A reduction in the TDE error consequently leads to a reduction in the control error.

D. Controller design

To stabilize a nonlinear system, we construct the control variable in the form

$$u = \frac{1}{\alpha} \left(y_d^{(n)} - \hat{F}(t) - k_0 \tilde{y} - k_1 \dot{\tilde{y}} - \ldots - k_{n-1} \tilde{y}^{(n-1)} \right), \tag{21}$$

where $\tilde{y} = y - y_d$ is the control error, and $k_0 ... k_{n-1}$ are the controller gains. Including the control variable (21) into (14) leads to the dynamics of the control error

$$y^{(n)} + k_{n-1} \tilde{y}^{(n-1)} + \ldots + k_1 \dot{\tilde{y}} + k_0 \tilde{y} = \tilde{F}(t), \tag{22}$$

where $\tilde{F}(t) = F(t) - \hat{F}(t)$ is the disturbance estimation error. Error dynamics (22) is stable for the choice of gains $k_0, k_1, ..., k_{n-1}$ that satisfy Routh/Hurwitz stability criterion, or for the gains obtained by the pole placement method. If the disturbance estimation error $\tilde{F}(t)$ is bounded, then the closed-loop system (22) represents a stable linear system with bounded input, implying bounded tracking error according to standard BIBO stability arguments.

IV. Simulation results

The effectiveness of the proposed control design is illustrated by the simulation examples. For the simulation purposes quadrotor system parameters are taken from [16]: moments of inertia are $I_x = I_y = 5 \cdot 10^{-3}$ kgm^2, $I_z = 8 \cdot 10^{-3}$ kgm^2, quadrotor arm length is $l = 0.14$ m, and maximal thrust force of one actuator is $f_{max} = 2.86$ N. It can be calculated that the maximal roll/pitch torque for this drone is $\tau_{\theta max} = 0.57$ Nm and maximal torque around z axis is $\tau_{\psi max} = 0.17$ Nm. It is assumed that a measurements of attitude angles and angle rates are available. Attitude control tests are performed in two cases:

- Case 1: task is to stabilize attitude angles in the presence of the unknown external disturbances.
- Case 2: task is to follow desired attitude trajectory in the presence of the unknown external disturbances.

The ATDC controller parameters are calculated by pole placement method with multiple pole in $s = -4$. Parameter α is set to be reciprocal value of inertia moment. Regarding equation (19), parameter $m = 2$, and order of estimation accuracy is

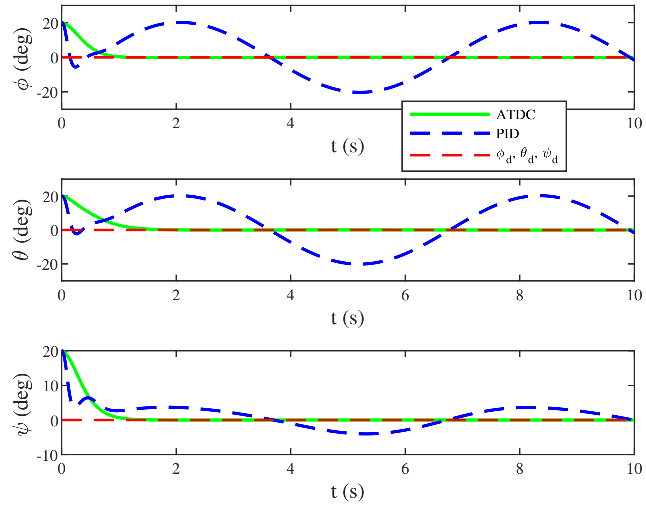

Fig. 2. Attitude stabilization in the presence of external disturbances (5% of the maximal actuator torque). Comparison of the ATDC and the linear PID controller.

set to $N = m + 1$. Time-delay parameter is set to $T = 50$ ms for both cases. State space variables (18) are assumed to be initialized to zero. Proposed control design is also compared to existing disturbance compensation control algorithms TDC and ADRC ESO.

A. Case 1

Initial values of three attitude angles are set to 20 deg, while desired roll, pitch and yaw angles are set to be zero. Periodic external disturbances (external torques) are applied to all three attitude axis in a form:

$$\begin{aligned} \tau_\phi &= \tau_\theta = 0.8\, \tau_{\theta \max}\, \sin(t) \;\; [\text{Nm}], \\ \tau_\psi &= 0.8\, \tau_{\psi \max}\, \sin(t) \;\; [\text{Nm}], \end{aligned} \tag{23}$$

where the maximal external torque considered is equal to the 80% of the maximal actuator torque. Fig. 2 shows comparison of the linear PID controller without disturbance compensation and the proposed algebraic TDC with disturbance compensation. It can be noted that PID can not stabilize the attitude angles even when small external disturbance affect the system (5% of the maximal actuator torque in this case). Performance comparison of algebraic TDC to existing TDC and ADRC controllers is presented in Fig. 3. It can be seen that ATDC provides asymptotic convergence toward constant reference state. On the other hand, conventional TDC and ADRC methods can't compensate high-frequency disturbances completely, thus not achieving asymptotic convergence for roll and pitch angles. ATDC algorithm estimated total disturbance (internal and external disturbances affecting the quadrotor) with good accuracy even not having prior information about it, as seen in Fig. 4. Fig. 5 shows smooth ATDC control variables, which values are in range of the maximal torques that our drone can achieve.

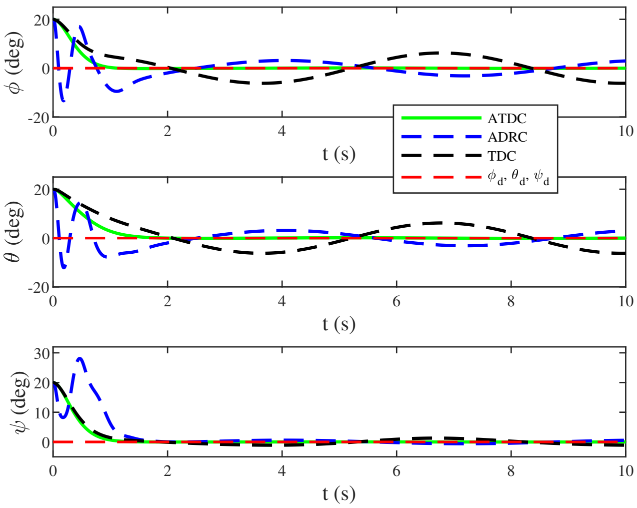

Fig. 3. Case 1: attitude stabilization in the presence of external disturbances. Comparison of the ATDC, TDC and ADRC control methods.

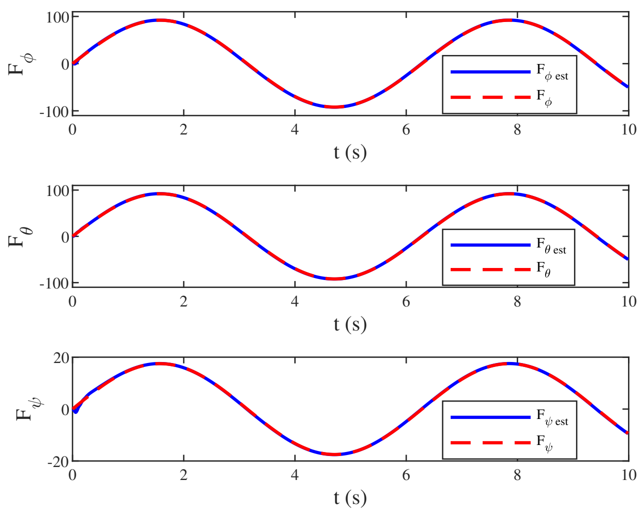

Fig. 4. Case 1: Total disturbance estimation by the ATDC, for $N = 3$.

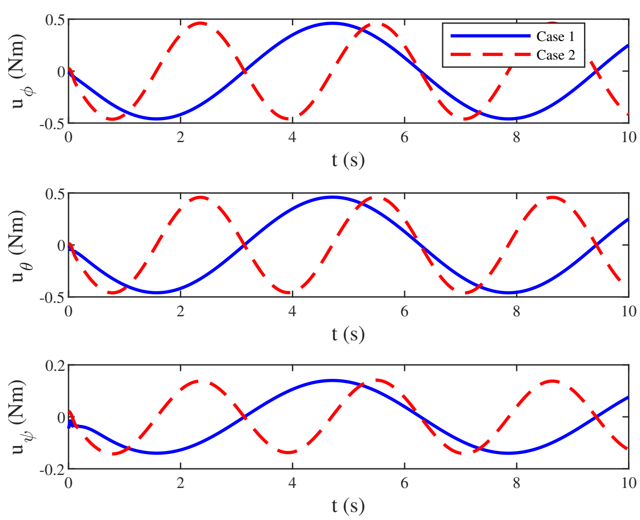

Fig. 5. Control variables/torques of three attitude axis for case 1 and case 2.

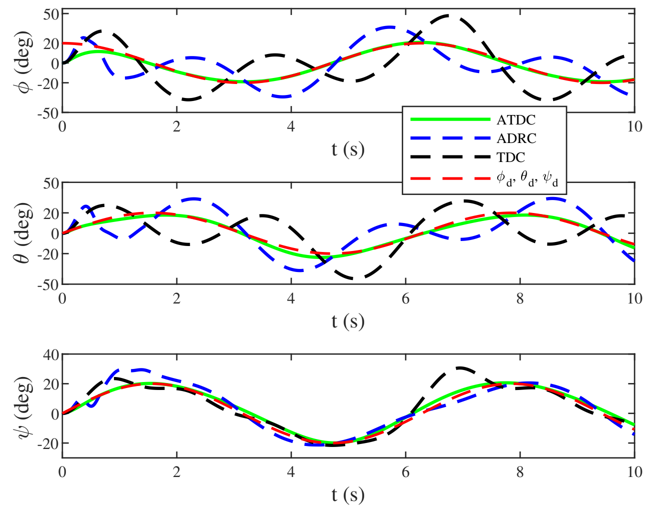

Fig. 6. Case 2: attitude trajectory tracking in the presence of external disturbances. Comparison of the ATDC, TDC and ADRC control methods.

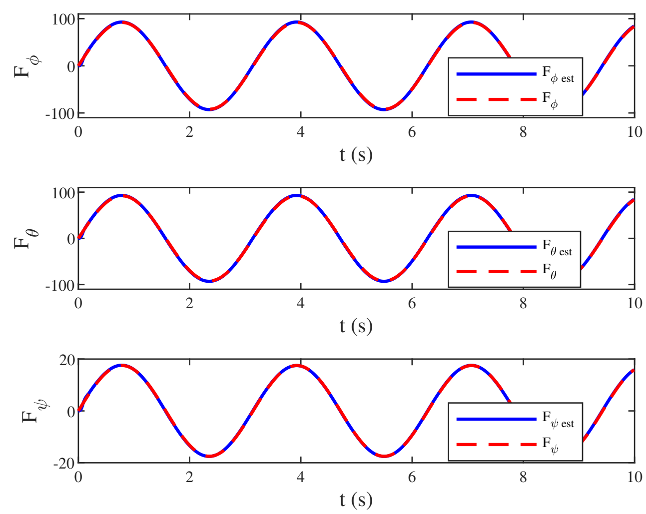

Fig. 7. Case 2: Total disturbance estimation by the ATDC, for $N = 3$.

B. Case 2

In this scenario quadrotor has a task to follow time variant attitude reference. Reference signals with maximal amplitude of 20 deg are in a form:

$$\begin{aligned} \phi_d &= 20\ \cos(t)\ \ [\text{deg}], \\ \theta_d = \psi_d &= 20\ \sin(t)\ \ [\text{deg}]. \end{aligned} \tag{24}$$

External disturbances have larger frequencies in this case:

$$\begin{aligned} \tau_\phi = \tau_\theta &= 0.8\, \tau_{\theta\max}\ \sin(2t)\ \ [\text{Nm}], \\ \tau_\psi &= 0.8\, \tau_{\psi\max}\ \sin(2t)\ \ [\text{Nm}]. \end{aligned} \tag{25}$$

Fig. 6 shows that proposed ATDC has the best tracking performance, while the conventional TDC and ADRC have large overshoots especially in roll/pitch angles. Total disturbance estimation by ATDC for case 2 is presented in Fig. 7. Bounded controller outputs for this case are also depicted in Fig. 5. For the purpose of assessing the quality of disturbance estimation (Fig. 4 and Fig. 7), there was a need to model a total disturbance for our quadrotor attitude system. From equations (1), (2) and (14) total disturbance can be modeled as (Pitch axis example):

$$F_\theta = \frac{I_z - I_x}{I_y}\,\dot{\phi}\,\dot{\psi} + \left(\frac{1}{I_y} - \alpha_\theta\right) u_\theta + \frac{\tau_\theta}{I_y}. \qquad (26)$$

In equation (26) first two terms represents internal dynamics of the system, while the last term represents external forces affecting the drone.

C. Adjustable order of estimation accuracy

Fig. 8 shows that by every increase of accuracy order N by 1, estimation accuracy is better by order of magnitude. This part was tested within a case 1 settings, and results presented for 1 DOF (Pitch angle). The improvement with increasing N shown here is obtained in the considered noiseless simulation setting.

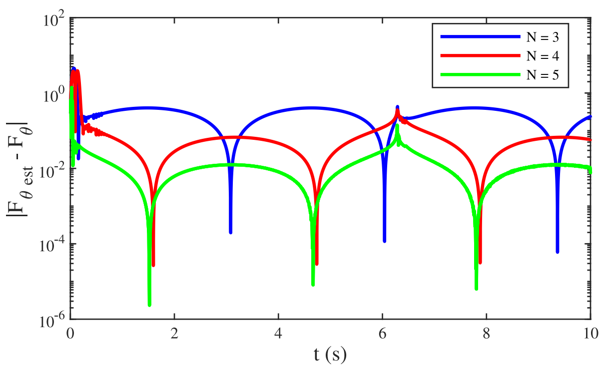

Fig. 8. Dependence of disturbance estimation accuracy on the estimation order N (Pitch angle, Case 1).

V. Conclusion

In this paper, an algebraic time-delay control (ATDC) algorithm is proposed, with application to quadrotor attitude control. The main advantage of the proposed method lies in its estimator, which can achieve arbitrary adjustable estimation accuracy of unmodeled dynamics while maintaining a simple linear controller structure, thereby simplifying both the design and implementation. Simulation results demonstrate that ATDC outperforms conventional time-delay control (TDC) and active disturbance rejection control (ADRC) methods. Since higher-order differentiation inherently amplifies measurement noise, the practically achievable estimation order N is limited by noise sensitivity. Future work will focus on noise-robust implementations of the ATDC estimator, including filtering techniques.

Acknowledgment

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