Adaptive Integral-Type Terminal Sliding Mode Control for Unmanned Aerial Vehicle Under Model Uncertainties and External Disturbances

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ABSTRACT This paper proposes an adaptive integral-type terminal sliding mode approach for the attitude and position tracking control of a quadrotor UAV subject to model uncertainties and external disturbances. First, an integral-type terminal sliding tracker is designed to attain the quadrotor UAV tracking performance in finite time when the upper bound of perturbations and uncertainties are known. Next, an adaptation law is proposed and a modified parameter-tuning integral-type terminal sliding mode tracking control scheme is designed to compensate of the model uncertainties and external disturbances. The stability and finite time convergence of the proposed approach is verified using the Lyapunov theory. Its performance is assessed using a simulation study encompassing various scenarios. Low chattering dynamics, fast convergence rate, and absence of singularities are the main features of the proposed approach.

INDEX TERMS Quadrotor UAV, finite time control, adaptive law, model uncertainty and external disturbance, integral-type terminal sliding surface.

I. INTRODUCTION
Unmanned Aerial Vehicles (UAVs), especially quadrotors, are widely popular due to their simple and ordinary structure, small size, low maintenance cost and, high hovering accuracy [1], [2]. They have been considered in a wide range of applications including; energy transportation streaks’ control [3], organizing requirements of military missions [4], surveillance [5], monitoring [6], [7], search and rescue [8], [9], agriculture [10], [11]. Tracking and stability control of quadrotors, however, is a challenging problem that has motivated various research efforts [12], [13]. This is due to the fact that quadrotors are under-actuated systems with no natural stabilizing elements, that are often operating under unfamiliar and uncertain flight conditions. Thus advanced estimation and control algorithms are required to control the quadcopter.

One of the effective methods to control quadrotors is the Terminal Sliding Mode control (TSMC) which offers both fast reachability of the quadrotor trajectories and high robustness against disturbances [14], [15]. The TSMC can be combined with an adaptive control procedure for the approximation of the upper bound of uncertainties and disturbances to further improve its performance in the presence of uncertainties and disturbances [16], [17].

In [18], a robust adaptive SMC method was proposed for the control of quadrotors in the presence of external disturbances and uncertainties. Though the approach achieved good tracking performance, the finite-time convergence of the attitude and position tracking was not considered in this work. In [19], an appointed-finite-time controller is presented for the attitude tracking control of a quadrotor in the presence of external disturbances. A terminal sliding mode observer was recommended for the estimation of the disturbances at any moment. However, this approach only examined the attitude tracking of the quadrotor and did not consider position tracking. In [20], a robust global SMC approach is proposed for the attitude tracking control of the quadrotor in the presence of external disturbances. An adaptive law is considered to estimate the upper bound of the external disturbances. Position tracking, however, was not investigated in this work. In [21], an adaptive fast SMC is designed for the control of a quadrotor under wind gust conditions. An adaptive law is applied for the reduction of the chattering phenomenon. In [22], a SMC method is presented for control of the quadrotor in the presence of the disturbances. An adaptive fuzzy control approach is adopted to compensate for the
disturbances. In [23], a fast TSMC scheme is designed for the hovering control of UAVs in the presence of obstacles. An adaptive control procedure is considered to compensate for these obstacles. Nonetheless, model uncertainties were not considered in these works. In [24], an integral TSMC approach is proposed for the tracking control of the quadrotor in the presence of uncertainties, external disturbances and faults. The proposed approach was combined with an adaptive control technique to elimination the need for any knowledge about the upper bound of disturbances and uncertainties. The model of the quadrotor considered in that paper, however, is the simplified 4DoF model, which is not appropriate in practice. In [25], an adaptive fractional-order fast TSMC approach was proposed for the attitude tracking control of a quadrotor subject to external disturbances and uncertainties. However, the impact of measurement noise on the control method was not examined in the above mentioned paper.

Based on the above discussion, this paper proposes an adaptive integral-type terminal sliding mode control approach for the attitude and position tracking control of a quadrotor UAV subject to model uncertainties and external disturbances. The main contributions of this paper are as follows:

- A robust controller designed for a realistic 6DoF quadrotor UAV with model uncertainties, external disturbances;
- A parameter-tuning law to estimate the upper bound of model uncertainties and external disturbances in integral-type terminal sliding mode controller;
- A design that yields finite time tracking, rapid convergence speed and control signals that are free of singularities and exhibit low chattering.
- Dynamic analysis in the presence of noise measurement.

The remainder of the paper is organized as follows. Section II introduces the dynamic model of the 6DoF UAV. Section III formulates the control problem and provides some preliminaries. The proposed control approach is derived in section IV. Computer simulations illustrating the performance of the proposed approach are given in section V. Some conclusions are finally drawn in section VI.

II. MODELING OF THE 6DOF QUADROTOR SYSTEM

Quadrotors are Vertical Take-Off and landing vehicles which have four control inputs. Their control is typically realized via the angular speed of the four propellers. These latter can generate thrust, pitching, rolling and yawing moments as shown in Figure 1 [26]. Quadrotors are under-actuated systems. This is due to the fact that six states are being controlled by four control inputs.

The dynamics of a quadrotor with 6DoF can be represented by [27], [28]:

\[
\begin{align*}
\ddot{x} &= \frac{1}{m} \left[ -K_{fdx} \dot{x} + (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)u_1 \right], \\
\ddot{y} &= \frac{1}{m} \left[ -K_{fdy} \dot{y} + (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi)u_1 \right], \\
\ddot{z} &= \frac{1}{m} \left[ -K_{fdz} \dot{z} + (\cos \phi \cos \theta)u_1 \right] - g,
\end{align*}
\]

where, the variables \( x, y, z \) represent the position coordinates of the quadrotor and \( \phi, \theta, \psi \) are the attitude of the quadrotor. \( m \) is the mass and \( d \) is the distance between the rotation axes and the center of the quadrotor. The terms \( K_{fdx}, K_{fdy}, K_{fdz} \) are the drag coefficients and \( K_{faz}, K_{fay}, K_{fas} \) denote the aerodynamic fiction factors. Also, \( C_D \) and \( J_i \) are the drag factors and motor inertia, respectively. The expressions \( I_x, I_y, I_z \) denote the inertia to the axes \( x, y, z \), respectively. \( u_i (i = z, \phi, \theta, \psi) \) are the control inputs.

\[
\begin{align*}
\ddot{\phi} &= \frac{1}{I_x} \left[ (I_y - I_z) \dot{\psi} \dot{\theta} - K_{fas} \dot{\phi}^2 - J_x \ddot{\psi} + d u_2 \right], \\
\ddot{\theta} &= \frac{1}{I_y} \left[ (I_z - I_x) \dot{\phi} \dot{\psi} - K_{fas} \dot{\theta}^2 + J_y \ddot{\phi} + d u_3 \right], \\
\ddot{\psi} &= \frac{1}{I_z} \left[ (I_x - I_y) \dot{\phi} \dot{\theta} - K_{fas} \dot{\psi}^2 + C_D u_4 \right].
\end{align*}
\]

FIGURE 1. Thrust and moments of the quadrotor [29].
III. PROBLEM FORMULATION AND PRELIMINARIES

Considering \( x(t) = [\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}, x, \dot{x}, y, \dot{y}, z, \dot{z}]^T \) as the state vector and \( u(t) = [u_2, u_3, u_4, u_1]^T \) as the input vector, the dynamics of the 6DOF quadrotor (4) can be represented using the following state space model:

\[
\dot{x}(t) = f(x(t)) + g(x(t))u(t) + d(t),
\]

where \( f(x(t)) \) and \( g(x(t)) \) are defined by:

\[
f(x(t)) = \begin{bmatrix}
x_2 \\
a_1x_4x_6 + a_2x_2^2 + a_3x_4 \\
x_4 \\
a_4x_2x_6 + a_5x_4^2 + a_6x_2 \\
x_6 \\
a_7x_2x_4 + a_8x_6 \\
x_8 \\
a_9x_8 \\
x_{10} \\
a_{10}x_{10} \\
x_{12} \\
a_{11}x_{12} - g
\end{bmatrix},
\]

\[
g(x(t)) = [g_1, g_2, g_3, g_4] = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix}\tag{7}
\]

with \( a_1 = \frac{l_2-l_4}{l_4}, a_2 = -\frac{K_{a1}}{l_4}, a_3 = \frac{l_4-l_2}{l_4}, a_4 = \frac{l_2-l_4}{l_4}, a_5 = -\frac{K_{a2}}{l_4}, a_6 = \frac{l_2-l_4}{l_4}, a_7 = \frac{l_4-l_2}{l_4}, a_8 = -\frac{K_{a3}}{l_4}, a_9 = -\frac{K_{a4}}{l_4}, a_{10} = -\frac{K_{a5}}{l_4}, a_{11} = -\frac{K_{a6}}{l_4}, b_1 = \frac{d}{l_4}, b_2 = \frac{d}{l_4} \) and \( b_3 = \frac{c_2}{l_4} \). The vector \( d(t) = [d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8, d_9, d_{10}, d_{11}, d_{12}]^T \) represents system uncertainties and external disturbances.

The main control objective is to design a sliding mode-based position and attitude tracking controller for the 6DoF quadrotor subject to model uncertainties and external disturbances that: 1) guarantees finite time convergence, 2) is free of singularities, 3) exhibit high chattering.

The following assumptions and lemmas are considered:

**Assumption 1:** Assuming the model uncertainties \( d_i, i = 1, 3, 5, 7, 9 \) and external disturbances \( d_i, i = 2, 4, 6, 8, 10, 12 \) are bounded by positive constants \( \delta_1, \ldots, \delta_{12} \) such that

\[
|\eta_2d_1 + d_2| \leq \delta_2, |\eta_3d_3 + d_4| \leq \delta_3, |\eta_4d_5 + d_6| \leq \delta_4, |\eta_5d_7 + d_8| \leq \delta_5, |\eta_6d_9 + d_{10}| \leq \delta_6 \text{ and } |\eta_7d_{11} + d_{12}| \leq \delta_1.
\]

**Lemma 1:** The Lyapunov function \( V(t) \) is a continuous positive-definite function which satisfies the following differential inequality [30]:

\[
\dot{V}(t) \leq -mV^n(t) - nV(t),
\]

where \( m \) and \( n \) are positive constants, \( \eta = \frac{2}{n} \) is a constant parameter, and \( a, b \) are odd positive integers that satisfy \( 0 < a < b \). Then, the function \( V(t) \) converges to zero in the finite time \( t_f \):

\[
t_f \leq t_0 + \frac{1}{n(1-\eta)} \ln(nV^n(t_0) + m).
\]

where \( t_0 \) is the initial time.

The output of the quadrotor UAV system is considered as \( y(t) = [\phi, \theta, \psi, x, y, z]^T \). The tracking error signals are expressed by:

\[
e_{\phi_1}(t) = y_1(t) - \phi(t) e_{\phi_1}(t) = \dot{y}_1(t) - \dot{\phi}(t) \tag{10}
\]

\[
e_{\theta_1}(t) = y_2(t) - \theta(t) e_{\theta_1}(t) = \dot{y}_2(t) - \dot{\theta}(t) \tag{11}
\]

\[
e_{\psi}(t) = y_3(t) - \psi(t) e_{\psi}(t) = \dot{y}_3(t) - \dot{\psi}(t) \tag{12}
\]

\[
e_{x_1}(t) = y_4(t) - x(t) e_{x_1}(t) = \dot{y}_4(t) - \dot{x}(t) \tag{13}
\]

\[
e_{y_1}(t) = y_5(t) - y(t) e_{y_1}(t) = \dot{y}_5(t) - \dot{y}(t) \tag{14}
\]

\[
e_{z_1}(t) = y_6(t) - z(t) e_{z_1}(t) = \dot{y}_6(t) - \dot{z}(t) \tag{15}
\]

where \( [\phi_1(t), \theta_1(t), \psi_1(t), x_1(t), y_1(t), z_1(t)] \) is the desired output vector.

Define the integral-type TSMC surfaces as:

\[
s_2(t) = e_{\phi_2}(t) + \eta_2 e_{\phi_2}(t) + \kappa_2 \int_0^t e_{\phi_1}(t)^{q_2/p_2} d\tau, \tag{16}
\]

\[
s_3(t) = e_{\theta_2}(t) + \eta_3 e_{\theta_2}(t) + \kappa_3 \int_0^t e_{\theta_1}(t)^{q_3/p_3} d\tau, \tag{17}
\]

\[
s_4(t) = e_{\psi}(t) + \eta_4 e_{\psi}(t) + \kappa_4 \int_0^t e_{\psi}(t)^{q_4/p_4} d\tau, \tag{18}
\]

\[
s_5(t) = e_{x_1}(t) + \eta_5 e_{x_1}(t) + \kappa_5 \int_0^t e_{x_1}(t)^{q_5/p_5} d\tau, \tag{19}
\]

\[
s_7(t) = e_{y_1}(t) + \eta_7 e_{y_1}(t) + \kappa_7 \int_0^t e_{y_1}(t)^{q_7/p_7} d\tau, \tag{20}
\]

\[
s_i(t) = e_{z_1}(t) + \eta_i e_{z_1}(t) + \kappa_i \int_0^t e_{z_1}(t)^{q_i/p_i} d\tau, \tag{21}
\]

where \( \eta_i \) and \( \kappa_i, i = 2, 3, 4, x, y, z \) are positive scalars, and \( q_i \) and \( p_i \) are two odd positive integers with \( q_i < p_i \). If the initial errors are equal to zero, then the tracking problem is assumed to be the error remaining on switching surfaces \( s_i(t) = 0, i = 2, 3, 4, x, y, z \) for \( \tau \geq 0 \). If the error states reach the sliding manifold \( s_i(t) = 0, i = 2, 3, 4, x, y, z \), they stay on it while sliding to \( e_i(t) = 0 \) and \( \dot{e}_i(t) = 0 \).

Differentiating the above sliding surfaces with respect to time, one finds:

\[
\dot{s}_2(t) = \dot{e}_{\phi_2}(t) + \eta_2 \ddot{e}_{\phi_2}(t) + \kappa_2 e_{\phi_2}(t)^{q_2/p_2}, \tag{22}
\]

\[
\dot{s}_3(t) = \dot{e}_{\theta_2}(t) + \eta_3 \ddot{e}_{\theta_2}(t) + \kappa_3 e_{\theta_2}(t)^{q_3/p_3}, \tag{23}
\]

\[
\dot{s}_4(t) = \dot{e}_{\psi}(t) + \eta_4 \ddot{e}_{\psi}(t) + \kappa_4 e_{\psi}(t)^{q_4/p_4}, \tag{24}
\]

\[
\dot{s}_5(t) = \dot{e}_{x_1}(t) + \eta_5 \ddot{e}_{x_1}(t) + \kappa_5 e_{x_1}(t)^{q_5/p_5}, \tag{25}
\]

\[
\dot{s}_7(t) = \dot{e}_{y_1}(t) + \eta_7 \ddot{e}_{y_1}(t) + \kappa_7 e_{y_1}(t)^{q_7/p_7}, \tag{26}
\]

\[
\dot{s}_i(t) = \dot{e}_{z_1}(t) + \eta_i \ddot{e}_{z_1}(t) + \kappa_i e_{z_1}(t)^{q_i/p_i}, \tag{27}
\]
Substituting Eqs. (5)-(7 and (10)-(15) in the above equations, yields:

\[
\dot{s}_2(t) = a_1 x_4 x_6 + a_2 x_2^2 + a_3 \dot{\Omega}_x - \dot{\phi}_d(t) + \eta_2 (x_2 - \dot{\phi}_d(t)) + \kappa_2 e_{\phi_1}(t) \frac{\eta_2}{\mu} + \eta_2 d_1 + d_2 + b_1 u_2,
\]

\[
\dot{s}_3(t) = a_4 x_2 x_6 + a_5 x_4^2 + a_6 \dot{\Omega}_x - \dot{\psi}_d(t) + \eta_3 (x_4 - \dot{\psi}_d(t)) + \kappa_3 e_{\psi_1}(t) \frac{\eta_3}{\mu} + \eta_3 d_1 + d_4 + b_2 u_3,
\]

\[
\dot{s}_4(t) = a_7 x_2 x_4 + a_8 x_6^2 - \ddot{\psi}_d(t) + \eta_4 (x_6 - \dot{\psi}_d(t)) + \kappa_4 e_{\psi_1}(t) \frac{\eta_4}{\mu} + \eta_4 d_7 + d_8 + b_3 u_4,
\]

\[
\dot{s}_5(t) = a_9 x_8 + \eta_5 (x_8 - \ddot{x}_d(t)) - \ddot{x}_d(t) + \kappa_5 e_{x_1}(t) \frac{\eta_5}{\mu} + \eta_5 d_9 + d_10 + \frac{u_5}{m} + u_1,
\]

\[
\dot{s}_6(t) = a_{10} x_{12} - g - \ddot{z}_d(t) + \eta_6 (x_{12} - \ddot{z}_d(t)) + \kappa_6 e_{z_1}(t) \frac{\eta_6}{\mu} + \eta_6 d_{11} + d_{12} + \frac{c_{x_1} c_{x_2}}{m} + u_1.
\]

Now, the equivalent controller \( u_{eq}, i = 2, 3, 4, x, y, 1 \) can be obtained from equation \( \dot{s}_i(t) = 0, (i = 2, 3, 4, x, y, 1) \) as:

\[
u_{eq_2} = -b_1^{-1} (a_1 x_4 x_6 + a_2 x_2^2 + a_3 \dot{\Omega}_x - \dot{\phi}_d(t) + \eta_2 (x_2 - \dot{\phi}_d(t)) + \kappa_2 e_{\phi_1}(t) \frac{\eta_2}{\mu} )
\]

\[
u_{eq_3} = -b_2^{-1} (a_4 x_2 x_6 + a_5 x_4^2 + a_6 \dot{\Omega}_x - \dot{\psi}_d(t) + \eta_3 (x_4 - \dot{\psi}_d(t)) + \kappa_3 e_{\psi_1}(t) \frac{\eta_3}{\mu} ), \]

\[
u_{eq_4} = -b_3^{-1} (a_7 x_2 x_4 + a_8 x_6^2 - \ddot{\psi}_d(t) + \eta_4 (x_6 - \dot{\psi}_d(t)) + \kappa_4 e_{\psi_1}(t) \frac{\eta_4}{\mu} ),
\]

\[
u_{eq_5} = \frac{-m}{u_1} (a_9 x_8 + \eta_5 (x_8 - \ddot{x}_d(t)) - \dot{x}_d(t) + \eta_5 d_7 + \kappa_5 e_{x_1}(t) \frac{\eta_5}{\mu} + \eta_5 d_8 + d_8 + \frac{u_5}{m} + u_1),
\]

\[
u_{eq_6} = \frac{-m}{u_1} (a_{10} x_{12} - g - \ddot{z}_d(t) + \eta_6 (x_{12} - \ddot{z}_d(t)) - \dot{z}_d(t) + \eta_6 d_9 + d_10 + \frac{c_{x_1} c_{x_2}}{m} + u_1).
\]

The total control input is defined as

\[
u_i = u_{eq} + u_{T_i} \ (\forall i = 2, 3, 4, x, y, 1),
\]

where \( u_{T_i} \)'s are obtained based on the adaptive integral-type TSMC method described in the next section.

**IV. PROPOSED CONTROL APPROACH**

In what follows, an integral-type TSMC-based finite time tracking control approach is first derived with the assumption that the upper bounds of uncertainties and disturbances are known. Then, an adaptive integral-type TSMC approach is synthesized for the case when the upper bounds of perturbations and model uncertainties are assumed to be unknown.

**A. FINITE-TIME INTEGRAL-TYPE TSMC DESIGN**

The integral-type TSMC controller is defined as:

\[
u_{T_2} = -b_1^{-1} (\lambda_2 s_2(t) + \gamma_2 \left| s_2(t) \right| a_{s_2} \text{sgn}(s_2(t)) \left| a_{s_2} \text{sgn}(s_2(t)) \right|)
\]

\[
u_{T_3} = -b_2^{-1} (\lambda_3 s_3(t) + \gamma_3 \left| s_3(t) \right| a_{s_3} \text{sgn}(s_3(t)) \left| a_{s_3} \text{sgn}(s_3(t)) \right|)
\]

\[
u_{T_4} = -b_3^{-1} (\lambda_4 s_4(t) + \gamma_4 \left| s_4(t) \right| a_{s_4} \text{sgn}(s_4(t)) \left| a_{s_4} \text{sgn}(s_4(t)) \right|)
\]

\[
u_{T_5} = -\frac{m}{u_1} (\lambda_5 s_5(t) + \gamma_5 \left| s_5(t) \right| a_{s_5} \text{sgn}(s_5(t)) \left| a_{s_5} \text{sgn}(s_5(t)) \right|)
\]

\[
u_{T_1} = -\frac{m}{c_{x_1} c_{x_2}} (\lambda_1 s_1(t) + \gamma_1 \left| s_1(t) \right| a_{s_1} \text{sgn}(s_1(t)) \left| a_{s_1} \text{sgn}(s_1(t)) \right|)
\]

where \( 0 < a_i < 1, \lambda_i > 0, \gamma_i > 0, i = 2, 3, 4, x, y, 1 \).

The finite-time convergence of the integral-type terminal sliding surfaces (16)-(21) is investigated using the following theorem:

**Theorem 1:** Consider the nonlinear 6DoF quadrotor UAV described using (5) with model uncertainties and external disturbances which satisfy Assumption 1. Let the error signal between the desired and actual outputs defined by (10)-(15). Then, the sliding surfaces (16)-(21) converge to the origin in finite time, if we consider the control inputs (40) with (34)-(39) as equivalent controls and (41)-(46) as the finite-time integral-type TSMC. Hence, the attitude and position tracking control of the quadrotor is satisfied.

**Proof:** Construct the Lyapunov function by

\[V_i(t) = 0.5 s_i(t)^2 \ (\forall i = 2, 3, 4, x, y, 1).\]

Taking the time-derivative of (47) and substituting \( s_i \) by (28)-(33), yields:

\[
\dot{V}_2(t) = s_2(t)(a_1 x_4 x_6 + a_2 x_2^2 + a_3 \dot{\Omega}_x - \dot{\phi}_d(t) + \eta_2 (x_2 - \dot{\phi}_d(t)) + \kappa_2 e_{\phi_1}(t) \frac{\eta_2}{\mu} + \eta_2 d_1 + d_2 + b_1 u_2)
\]

\[
\dot{V}_3(t) = s_3(t)(a_4 x_2 x_6 + a_5 x_4^2 + a_6 \dot{\Omega}_x - \dot{\psi}_d(t) + \eta_3 (x_4 - \dot{\psi}_d(t)) + \kappa_3 e_{\psi_1}(t) \frac{\eta_3}{\mu} + \eta_3 d_3 + d_4 + b_2 u_3)
\]

\[
\dot{V}_4(t) = s_4(t)(a_7 x_2 x_4 + a_8 x_6^2 - \ddot{\psi}_d(t) + \eta_4 (x_6 - \dot{\psi}_d(t)) + \kappa_4 e_{\psi_1}(t) \frac{\eta_4}{\mu} + \eta_4 d_7 + d_8 + \frac{u_5}{m} + u_1)
\]

\[
\dot{V}_5(t) = s_5(t)(a_9 x_8 + \eta_5 (x_8 - \ddot{x}_d(t)) - \ddot{x}_d(t) + \kappa_5 e_{x_1}(t) \frac{\eta_5}{\mu} + \eta_5 d_9 + d_10 + \frac{c_{x_1} c_{x_2}}{m} + u_1)
\]

\[
\dot{V}_6(t) = s_6(t)(a_{10} x_{12} - g - \ddot{z}_d(t) + \eta_6 (x_{12} - \ddot{z}_d(t)) - \dot{z}_d(t) + \kappa_6 e_{z_1}(t) \frac{\eta_6}{\mu} + \eta_6 d_9 + d_10 + \frac{c_{x_1} c_{x_2}}{m} + u_1).
\]

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where using Assumption 1 and some simplifications, yields:
\[
\dot{V}_1(t) = s_1(t) a_{11} x_{12} - g - \dot{z}_d(t) + \eta_1 (x_{12} - \hat{z}_d(t)) + \eta_1 d_{11} + d_{12} + \frac{\cos x_1 \cos x_3}{m} u_1 \tag{53}
\]

Substituting (40) with the usage of (34)-(39) and (41)-(46), yields:
\[
\begin{align*}
\dot{V}_2(t) &= s_2(t) \eta_2 d_1 + d_2 - \lambda_2 s_2(t) \\
&- \gamma_2 |s_2(t)|^{\alpha_2} \text{sgn}(s_2(t)) - \delta_2 \text{sgn}(s_2(t)) \tag{54} \\
\dot{V}_3(t) &= s_3(t) \eta_3 d_3 + d_4 - \lambda_3 s_3(t) \\
&- \gamma_3 |s_3(t)|^{\alpha_3} \text{sgn}(s_3(t)) - \delta_3 \text{sgn}(s_3(t)) \tag{55} \\
\dot{V}_4(t) &= s_4(t) \eta_4 d_4 + d_5 - \lambda_4 s_4(t) \\
&- \gamma_4 |s_4(t)|^{\alpha_4} \text{sgn}(s_4(t)) - \delta_4 \text{sgn}(s_4(t)) \tag{56} \\
\dot{V}_5(t) &= s_5(t) \eta_5 d_5 + d_6 - \lambda_5 s_5(t) \\
&- \gamma_5 |s_5(t)|^{\alpha_5} \text{sgn}(s_5(t)) - \delta_5 \text{sgn}(s_5(t)) \tag{57} \\
\dot{V}_6(t) &= s_6(t) \eta_6 d_6 + d_7 - \lambda_6 s_6(t) \\
&- \gamma_6 |s_6(t)|^{\alpha_6} \text{sgn}(s_6(t)) - \delta_6 \text{sgn}(s_6(t)) \tag{58} \\
\dot{V}_7(t) &= s_7(t) \eta_7 d_7 + d_8 - \lambda_7 s_7(t) \\
&- \gamma_7 |s_7(t)|^{\alpha_7} \text{sgn}(s_7(t)) - \delta_7 \text{sgn}(s_7(t)) \tag{59}
\end{align*}
\]

where using Assumption 1 and some simplifications, yields:
\[
\dot{V}_i \leq -\lambda_i s_i^2 - \gamma_i |s_i|^{\alpha_i + 1}, \quad i = 2, 3, 4, x, y, 1 \tag{60}
\]

According to the Lyapunov function (47), one obtains:
\[
\dot{V}(s) \leq -2 \lambda_1 V(s) - \frac{\alpha_i + 1}{2} \gamma_i V(s) \tag{61}
\]

Considering the Lemma 1, the terminal sliding mode surfaces (16)-(21) converge to the origin in finite time.

### B. Finit-Time Integral-Type SMC Design

In real applications, it is impossible to determine the upper bound of the model uncertainties and external disturbances \(d(t)\). To solve this problem, an estimation of the positive constant \(\delta_i\), i.e. \(\hat{\delta}_i(t)\) is considered.

Assume the estimation error as:
\[
\hat{\delta}_i(t) = \hat{\delta}_i(t) - \delta_i \quad (\forall i = 2, 3, 4, x, y, 1) \tag{62}
\]

### TABLE 1. Real parameters of the quadrotor.

| Parameters   | Value   | Parameters   | Value   |
|--------------|---------|--------------|---------|
| \(m(Kg)\)   | 0.486   | \(K_{r_x}(N/m rad/s^2)\) | 6.35404e-4 |
| \(d(m)\)    | 0.25    | \(K_{r_{ax}}(N/m rad/s^3)\) | 5.65707e-4 |
| \(I_y (Nm/m rad s^2)\) | 3.8278e-3 | \(K_{r_{ay}}(N/m rad/s^3)\) | 6.35404e-4 |
| \(I_x (Nm/m rad s^2)\) | 7.6566e-3 | \(K_{r_x}(N/m rad/s^3)\) | 2.98423e-3 |
| \(J_{r_{ax}} (N/m rad/s)\) | 5.56700e-4 | \(J_{r_{ay}} (N/m rad/s)\) | 3.23200e-2 |
| \(J_{r_{ay}} (N/m rad/s)\) | 5.56704e-4 | \(J_{r_{ax}} (N/m rad/s^2)\) | 2.83857e-5 |

By taking the time-derivative of \(\hat{\delta}_i(t)\), one finds:
\[
\dot{\hat{\delta}}_i(t) = \hat{\delta}_i(t) \tag{63}
\]

Now, the adaptation laws are defined as:
\[
\dot{\hat{\delta}}_i(t) = l_i^{-1} |s_i(e_i(t))| \tag{64}
\]

where \(l_i\) are positive constants. Subsequently, the adaptive integral-type TSMC controller is designed as:
\[
\begin{align*}
\dot{u}_{T_2} &= -b_1^{-1}((\hat{\delta}_2(t) + \mu_2 |s_2(t)|^{\xi_2} - v_2(\beta_2^{[s_2(t)]}) \\
&- 1) \text{sgn}(s_2(t))), \tag{65} \\
\dot{u}_{T_3} &= -b_2^{-1}((\hat{\delta}_3(t) + \mu_3 |s_3(t)|^{\xi_3} - v_3(\beta_3^{[s_3(t)]}) \\
&- 1) \text{sgn}(s_3(t))), \tag{66} \\
\dot{u}_{T_4} &= -b_3^{-1}((\hat{\delta}_4(t) + \mu_4 |s_4(t)|^{\xi_4} - v_4(\beta_4^{[s_4(t)]}) \\
&- 1) \text{sgn}(s_4(t))), \tag{67} \\
\dot{u}_{T_5} &= -b_4^{-1}((\hat{\delta}_5(t) + \mu_5 |s_5(t)|^{\xi_5} - v_5(\beta_5^{[s_5(t)]}) \\
&- 1) \text{sgn}(s_5(t))), \tag{68} \\
\dot{u}_{T_6} &= -b_5^{-1}((\hat{\delta}_6(t) + \mu_6 |s_6(t)|^{\xi_6} - v_6(\beta_6^{[s_6(t)]}) \\
&- 1) \text{sgn}(s_6(t))), \tag{69} \\
\dot{u}_{T_7} &= -b_7^{-1}((\hat{\delta}_7(t) + \mu_7 |s_7(t)|^{\xi_7} - v_7(\beta_7^{[s_7(t)]}) \\
&- 1) \text{sgn}(s_7(t))), \tag{70}
\end{align*}
\]
with $\mu_i, v_i > 0, 0 < \beta_i < 1$ and $\xi_i = \frac{c_i}{l_i}$ where $c_i, l_i$ are two odd numbers which satisfy the following condition $0 < c_i < l_i$.

In the following Theorem, the convergence of the sliding surfaces (16)-(21) is examined based on the adaptive integral-type sliding mode control scheme.

**Theorem 2:** Consider the nonlinear 6DoF quadrotor UAV system (5) in the presence of model uncertainties and external disturbances with unknown upper bounds. Also, let the error signal between the desired and actual trajectories as (10)-(15) and adaptive law as (64). Then, the sliding surfaces (16)-(21) converge to the origin considering the control inputs (40) with (34)-(39) as equivalent controls and (65)-(70) as integral-type TSMC controls. Therefore, the attitude and position tracking control of the quadrotor is achieved.

**Proof:** Consider the following Lyapunov function:
\[
V_i(s_i(t), \hat{\delta}_i(t)) = 0.5 \left[ s_i(t)^2 + l_i \tilde{\delta}_i(t)^2 \right],
\]
Taking the time-derivative of (71) and substituting the adaptation law (64), yields:
\[
\dot{V}_i(s_i(t), \hat{\delta}_i(t)) = \dot{s}_i(t) + \dot{\tilde{\delta}}_i(t) |s_i(t)|, 
\]
where using (28)-(33) in the above equation, yields:
\[
\dot{V}_2(s_2(t), \tilde{\delta}_2(t)) = s_2(t) [a_1 s_4 x_6 + a_2 s_2^2 + a_3 \tilde{\delta} x_4 - \tilde{\phi}_d(t) + \eta_2 (x_2 - \tilde{\phi}_d(t)) + \kappa_2 e_{\phi_1}(t)^{\frac{\gamma_2}{2}} + \eta_2 d_1 + d_2 + b_1 u_2] + \tilde{\delta}_2(t) |s_2(t)|
\]
\[
\dot{V}_3(s_2(t), \tilde{\delta}_3(t)) = s_3(t) [a_4 s_2 x_6 + a_5 s_2^2 + a_6 \tilde{\delta} v_2 - \tilde{\phi}_d(t) + \eta_3 (x_4 - \tilde{\phi}_d(t)) + \kappa_3 e_{\phi_1}(t)^{\frac{\gamma_3}{2}} + \eta_3 d_3 + d_4 + b_2 u_3] + \tilde{\delta}_3(t) |s_3(t)|
\]
\[ V_4(s_4(t), \tilde{\delta}_4(t)) = s_4(t)\alpha_7 \dot{x} + a_6 x_6 + a_9 x_9 \dot{y} \]
\[ + \eta_4 x_6 - \hat{\psi}_d(t) \]
\[ + \eta_4 d_5 + \beta_3 a_4 u_1 + \tilde{\delta}_4(t) |s_4(t)| \]
\[ \dot{V}_4(s_4(t), \tilde{\delta}_4(t)) = V_4(s_4(t), \tilde{\delta}_4(t)) - \dot{\tilde{\delta}}_4(t) \int_{0}^{t} \dot{u}(t) dt \]
(75)

\[ \dot{V}_x(s_x(t), \tilde{\delta}_x(t)) = s_x(t) |a_9 x_8 \nu_1 + \eta_4 (x_8 - \hat{x}_d(t)) \]
\[ - \tilde{x}_d(t) + \eta_4 d_4 + \beta_3 (u_1) \]
(76)

\[ \dot{V}_y(s_y(t), \tilde{\delta}_y(t)) = s_y(t) |a_10 x_10 \eta_4 (x_10 - \hat{y}_d(t)) \]
\[ - \tilde{y}_d(t) + \eta_4 d_4 + \beta_3 (u_1) \]
(77)

\[ \dot{V}_1(s_1(t), \tilde{\delta}_1(t)) = s_1(t) |(a_{11} x_{12} - g - \hat{z}_d(t)) \eta_1 (x_{12} - \hat{z}_d(t)) \]
\[ + \kappa_1 e_3(t) - \dot{\delta}_1(t) |s_1(t)| \]
(78)

Substituting the equivalent controls (34)-(39) and adaptive integral-type terminal sliding mode controller (65)-(70), one attains:

\[ \dot{V}_2(s_2(t), \tilde{\delta}_2(t)) = s_2(t) |\eta_2 d_1 + d_2 \]
\[ - (\hat{\delta}_2(t) + \mu_2 |s_2(t)|) \]
\[ + \tilde{\delta}_2(t) |s_2(t)| \]
(79)

\[ \dot{V}_3(s_3(t), \tilde{\delta}_3(t)) = s_3(t) |\eta_3 d_3 + d_4 \]
\[ - (\hat{\delta}_3(t) + \mu_3 |s_3(t)|) \]
\[ + \tilde{\delta}_3(t) |s_3(t)| \]
(80)

\[ \dot{V}_4(s_4(t), \tilde{\delta}_4(t)) = s_4(t) |\eta_4 d_5 + d_6 \]
\[ - (\hat{\delta}_4(t) + \mu_4 |s_4(t)|) \]
\[ + \tilde{\delta}_4(t) |s_4(t)| \]
(81)
\[ \dot{V}_i(s_x(t), \tilde{d}_x(t)) = \tilde{d}_x(t) |s_x(t)| + s_x(t)(\eta_x \delta_x + d_8) \\
- (\tilde{d}_x(t) + \mu_x |s_x(t)|) \delta_x \\
- v_i(\beta_1^{\delta_x(t)} - 1) \text{sgn}(s_x(t)) \\
+ \delta_x(t) |s_z(t)| \] (82)

\[ \dot{V}_y(s_y(t), \tilde{d}_y(t)) = \tilde{d}_y(t) |s_y(t)| + s_y(t)(\eta_y \delta_y + d_{10}) \\
+ (\tilde{d}_y(t) + \mu_y |s_y(t)|) \delta_y \\
- v_y(\beta_2^{\delta_y(t)} - 1) \text{sgn}(s_y(t)) \\
+ \delta_y(t) |s_z(t)| \] (83)

\[ \dot{V}_1(s_1(t), \tilde{d}_1(t)) = s_1(t)(\eta_x \delta_1 + d_{12}) \\
- (\tilde{d}_1(t) + \mu_1 |s_1(t)|) \delta_1 \\
- v_1(1-\beta_i^{\delta_1(t)}) |s_1(t)| + \tilde{d}_1(t) |s_1(t)| \] (84)

After consideration of the Assumption 1, the above equations can be written as:

\[ \dot{V}_i(s_i(t), \tilde{d}_i(t)) \leq \delta_i |s_i(t)| - \tilde{d}_i(t) |s_i(t)| - \mu_i |s_i(t)|^{\delta_i+1} \\
- v_i(1-\beta_i^{\delta_i(t)}) |s_i(t)| + \tilde{d}_i(t) |s_i(t)| \] (85)

Adding and subtracting the term \(\delta_i(t) |s_i(t)|\) to the right-hand-side of (85) and performing some simplifications yields:

\[ \dot{V}_i(s_i(t), \tilde{d}_i(t)) \leq -v_i\left(1-\beta_i^{\delta_i(t)}\right) |s_i(t)| - \mu_i |s_i(t)|^{\delta_i+1}. \] (86)

Hence, it is resulted that the Lyapunov function (71) decreases gradually, i.e., \(\dot{V}_i(s_i(t), \tilde{d}_i(t)) < 0\). This finalizes the proof of the theorem.

The block diagram of the proposed control approach is illustrated in FIGURE 2.

V. SIMULATION RESULTS

The performance of the proposed approach is illustrated using the quadrotor UAV which parameters are illustrated in Table 1. In addition, model uncertainties and external disturbances are considered as \(d_i = 0.1e^{-i+1}, i = 1, 3, 5, 7, 9\) and \(d_i = 0.25 \sin (\pi t) + 2, i = 2, 4, 6, 8, 10, 12\), respectively. Besides, the desired values with respect to the pitch, roll and yaw are selected as: \(\phi = \frac{\pi}{3} \sin(\frac{\pi}{3} t + 2), \theta = \frac{\pi}{6} \sin(\frac{\pi}{6} t + 2)\) and \(\phi = \frac{\pi}{4} \sin(\frac{\pi}{4} t + 2)\), respectively. Also, the desired values for \(x, y, z\) are chosen as \(0.5, 0.5, 1\), respectively. The initial condition of quadrotor states and adaption laws are considered as \(s_i(0) = 0.1(\forall i = 1, \ldots, 12)\) and \(\tilde{d}_i(0) = 0.1(\forall i = 2, 3, 4, x, y, 1)\). The controller parameters are illustrated in Table 2. These latter were obtained by trial and error. The finite-time value of \(t_{\phi}^i\) is calculated based on the inequality (9). The required values in (9) are considered as \(n_{\phi} = 2\lambda_{\phi} = 0.02, m_{\phi} = 2\lambda_{\phi+1} = 17.5, \eta = \frac{\alpha_{\phi+1}}{2} = 0.8, V_{\phi}(0) = 225\) and \(d_0 = 0.1\). Thus, based on the inequality (9), we have \(t_{\phi} \leq 0.85\). The other finite-time values can be calculated in a similar manner.

Three scenarios are considered in the performance analysis.
The time histories of the tracking errors are depicted in FIGURE 4. As it can be shown from these figures, the system states track the desired references appropriately and the tracking error signals reach zero in finite time. The time histories of the switching surfaces are displayed in FIGURE 5. The trajectories of the control inputs are depicted in FIGURE 6. It is observed from these figures that both sliding surfaces and control signals converge to the origin in finite time when using the proposed sliding mode control signal. Note also the appropriate amplitude and low chattering dynamics of the control inputs.

B. SIMULATION RESULTS WITH THE ADAPTIVE INTEGRAL-TYPE TSMC

This scenario examines the tracking performance of the adaptive terminal sliding mode technique. The time responses of the quadrotor UAV states are illustrated in FIGURE 7. The time trajectories of the tracking errors via adaptive terminal sliding mode controllers are displayed in FIGURE 8. One can conclude that the states track the desired references suitably and the tracking errors reach zero properly. The time histories of the terminal sliding surfaces and adaptive controller...
signals are given in FIGURE 9 and FIGURE 10, respectively. Furthermore, the time responses of the adaptive parameters are exhibited in FIGURE 11. As can be seen from these plots, the trajectories of the terminal sliding surfaces and control inputs converge to zero. One can observe that the obtained control signals do not exhibit any chattering and hence, the responses are chattering-free.

C. PERFORMANCE ANALYSIS IN THE PRESENCE OF MEASUREMENT NOISE

This scenario investigates the impact of measurement noise on the quadrotor system. A zero mean white noise with noise power 0.0001 and sample time 0.01 as shown in FIGURE 12 is added to the measurement. The time histories of the state tracking, sliding surfaces and control inputs in this case are illustrated in FIGURE 13, FIGURE 14 and FIGURE 15, respectively when using the integral-type TSMC. The same variables are displayed in FIGURE 16, FIGURE 17 and FIGURE 18 respectively, when using the adaptive integral-type TSMC. As one can observe, besides low chattering due to the noise, the simulation results are similar to the ones obtained without measurement noise.

VI. CONCLUSION

This paper proposed an adaptive terminal integral-type terminal sliding control procedure for the trajectory and position tracking of a quadrotor UAV subject to model uncertainties and external disturbances. A terminal integral-type sliding mode tracking control approach was recommended to achieve the trajectory tracking performance of this system with known bound for uncertainties and disturbances. Then, a modified adaptive integral-type terminal sliding mode tracker was proposed for the quadrotor UAVs with uncertainties and disturbances with unknown bounds. The simulation results showed that the proposed approach is free of singularities, exhibits low chattering dynamics and has fast convergence rate. The practical implementation of the proposed approach and its extension to the control of time-delayed quadrotor UAVs will be the focus of our future research.

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