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#### Two-Level Nonlinear Tracking Control of a Quadrotor Unmanned Aerial Vehicle Quadrotor Unmanned Aerial Vehicle  $T_{\text{N}}$   $\sim$   $T_{\text{N}}$  o-Level Ivonimear Tracking Control Nasrettin KÖKSAL\*, Hao AN\*\*, Barış FİDAN\* Two-Level Nonlinear Tracking Control of a Two-Level Nonlinear Tracking Control of a Quadrotor Unmanned Aerial Vehicle

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aerial vehicle (UAV) with a two-layer control architecture. In order to facilitate the control design, a decoupled dynamic model is derived for the quadrotor UAV. Backstepping method is employed to stabilize the closed-loop system and to achieve output tracking. The control structure has a high-level layer for producing the guiding state trajectories, and a low-level layer for tracking in both altitude and attitude dynamics. The designed control scheme can well handle the model nonlinearities as well as the drag effects, and can be directly implemented to produce the PWM control signals. Simulation results are provided to verify the efficiency of the proposed control scheme. Abstract: This study presents a nonlinear tracking control design for a quadrotor unmanned Abstract: This study presents a nonlinear tracking control design for a quadrotor unmanned

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Keywords: Quadrotor, Unmanned Aerial Vehicle, Backstepping Control. Keywords: Quadrotor, Unmanned Aerial Vehicle, Backstepping Control. Keywords: Quadrotor, Unmanned Aerial Vehicle, Backstepping Control.

#### 1. INTRODUCTION 1. INTRODUCTION 1. INTRODUCTION

Quadrotor unmanned aerial vehicle (UAV) systems, beguatified at a velocity systems, because of being capable to take off and land vertically and cause of being capable to take on and faild vertically and<br>hover at close proximity of specified locations in 3D as well nover at close proximity or specified focations in 5D as went<br>as having favorable accurate dynamic models and stability as having lavorable accurate dynamic models and stability characteristics, build compared to single rotor and fixedwing UAVs. Therefore, quadrotors have been popular for researchers and customers in the last decade. Develop-wing UAVs. Therefore, quadrotors have been popular for wing UAVs. Therefore, quadrotors have been popular for researchers and customers in the last decade. Developresearchers and customers in the last decade. Develop-<br>ments and performance requirements of quadrotors have ments and performance requirements or quadrotors have<br>been increased for difficult missions and environments in been increased for difficult infessions and environments in research studies and commercial use. Due to the simple research studies and commercial use. Due to the simple modular and motion capabilities, quadrotors have been used in various complicated indoor and outdoor tasks. modulat and motion capabilities, quadrotors have b Quadrotor unmanned aerial vehicle (UAV) systems, because of being capable to take off and land vertically and hover at close proximity of specified locations in 3D as well as having favorable accurate dynamic models and stability characteristics, build compared to single rotor and fixedwing UAVs. Therefore, quadrotors have been popular for researchers and customers in the last decade. Developments and performance requirements of quadrotors have been increased for difficult missions and environments in research studies and commercial use. Due to the simple modular and motion capabilities, quadrotors have been used in various complicated indoor and outdoor tasks.

In the literature, various methods from nonlinear control In the merature, various memous from nonmear control theory have been applied to motion control of quadrotors. design has been applied to motion control of quadrotors.<br>In Madani et al. (2006), a full state backstepping control In Madam et al. (2000), a fun state backstepping control<br>design has been applied to stabilize the system dynamics design has been applied to stabilize the system dynamics<br>and to track arbitrary reference trajectories. In Bouaband to track arbitrary reference trajectories. In Bouab-<br>dallah et al (2007), an integral backstepping control is  $\alpha$  factor  $\alpha$  and  $\alpha$  and  $\alpha$  feedback linearization-back linearization-based for position control of an autonomous quadroproposed for position control of an autonomous quadro-<br>tor. A feedback linearization-based controller is designed tof. A recuback inicialization-based controller is designed<br>together with high order sliding mode observer (SMO)  $\log$ ener with ligh order shang mode observer  $(SMO)$  against external disturbances such as wind and noise in against external distributions such as which and holse in<br>Benallegue et al (2008). Ryan et al (2013) presents a behangue et al (2006). Hyan et al (2013) presents a<br>linear matrix inequality (LMI) based control design usmear matrix mequanty (ENT) based control design us-<br>ing approximate feedback linearization. Lee et al (2013) ing approximate reedback inicarization. Lee et al (2013)<br>presents a global dynamic model for a quadrotor UAV, and presents a grobal dynamic model for a quadrotor  $\sigma$ AV, and<br>it develops robust nonlinear tracking controllers to avoid model based adaptive complex maneuver motions. A nonlinear singularities for complex maneuver motions. A nonlinear singulatives for complex maneuver motions. A nonlinear model based adaptive controller for attitude regulation is presented in Zeng et al (2011). As a nonlinear autonomous presented in Zeng et al (2011). As a nonlinear autonomous 1. INTRODUCTION control design, Choi et al (2015) presents a backstepping<br>Quadrotor unmanned occid well collapsed to the off-and and well controlly and the fall controlly and the set of the controlly and the controlly and In the literature, various methods from nonlinear control theory have been applied to motion control of quadrotors. In Madani et al. (2006), a full state backstepping control design has been applied to stabilize the system dynamics and to track arbitrary reference trajectories. In Bouabdallah et al (2007), an integral backstepping control is proposed for position control of an autonomous quadrotor. A feedback linearization-based controller is designed together with high order sliding mode observer (SMO) against external disturbances such as wind and noise in Benallegue et al (2008). Ryan et al (2013) presents a linear matrix inequality (LMI) based control design using approximate feedback linearization. Lee et al (2013) presents a global dynamic model for a quadrotor UAV, and it develops robust nonlinear tracking controllers to avoid singularities for complex maneuver motions. A nonlinear model based adaptive controller for attitude regulation is presented in Zeng et al (2011). As a nonlinear autonomous

 $\overline{\phantom{a}}$  . The work of N. K. Fidan is supported by the Canadian is support

control design, Choi et al  $(2015)$  presents a backsteppingtontrol design, Choi et al (2015) presents a backstepping-<br>like feedback linearization method to stabilize the quadrothe full automous meanization interiod to stabilize the quadro-<br>tor. Choi et al (2015) also implements its control design in the fully autonomous real-time tests. the fully autonomous real-time tests.  $\frac{1}{\sqrt{2}}$  we can see from the existing literature (Lee et al. tor. Unoi et al (2015) also implements its control design in<br>the fully autonomous real-time tests. control design, Choi et al (2015) presents a backsteppinglike feedback linearization method to stabilize the quadro-

As we can see from the existing literature (Lee et al As we can see nom the existing interactive (Lee et an  $(2013)$ ; Zeng et al  $(2011)$ ; Raffo et al  $(2010)$ ; Besnard (2013), Zeng et al  $(2011)$ , Kano et al  $(2010)$ , Beshard et al  $(2012)$ ; Choi et al  $(2015)$ ), it is not an easy task  $\alpha$  design a controller for the full motion dynamics of a to design a controller for the further implement dynamics of a quadrotor, including model nonlinearities and drag effects. quadrotor, including moder noninearities and drag enects.<br>It is also challenging to further implement the controller It is also channelling to further implement the controller<br>on a real system. In this study, the objective is to design of a real system. In this study, the objective is to design<br>a two level control scheme for tracking and stabilization a two lever control scheme for tracking and stabilization of a quadrotor UAV considering model nonlinearities and external drag effects. external drag effects. Compared with other related works (K¨oksal et al (2015); As we can see from the existing literature (Lee et al. (2012). (2013); Zeng et al (2011); Raffo et al (2010); Besnard et al (2012); Choi et al (2015)), it is not an easy task to design a controller for the full motion dynamics of a quadrotor, including model nonlinearities and drag effects. It is also challenging to further implement the controller on a real system. In this study, the objective is to design a two level control scheme for tracking and stabilization of a quadrotor UAV considering model nonlinearities and external drag effects.

Compared with other related works (Köksal et al (2015); Güler et al  $(2013)$ , the two-level control structure simpli-Guer et al (2013)), the two-level control structure simplifies the design process of the controller for a quadrotor. In this control scheme, the high-level control loop deals with this control scheme, the high-level control loop deals with the generation of the desired positions and attitude angles, attitude angles, while the low-level is responsible for the altitude and attitude dynamics of the quadrotor. To generate the conattitude dynamics of the quadrotor. To generate the con-<br>trol command that matches the pulse-width modulation (PWM) signals of the motor drivers, actuator dynamics (I WM) signals of the motor dirvers, actuator dynamics<br>are also considered at design level, which makes the deare also considered at design lever, which makes the designed controller more reliable. Both altitude and attitude controllers are designed using back-stepping method. controllers are designed using back-stepping method. The main advantage of the proposed control scheme over  $\mathbb{R}^n$ Compared with other related works (Koksal et al (2015);<br>Citler et al (2012)), the two-level sentrel structure simpliwhile the low-level is responsible for the altitude and<br>ettitude dynamics of the suadrotor. To generate the con-(PWM) signals of the motor drivers, actuator dynamics trol command that matches the pulse-width modulation fies the design process of the controller for a quadrotor. In this control scheme, the high-level control loop deals with the generation of the desired positions and attitude angles, are also considered at design level, which makes the designed controller more reliable. Both altitude and attitude controllers are designed using back-stepping method.

The main advantage of the proposed control scheme over the existing literature is decoupling the system dynamics into three sub-models. These sub-systems ease the control design and analysis for each sub-model separately. design and analysis for each sub-model separately. The rest of the study is organized as follows: the model is perfected as  $f(x)$ . the existing literature is decoupling the system dynamics The main advantage of the proposed control scheme over into three sub-models. These sub-systems ease the control design and analysis for each sub-model separately.

The rest of the study is organized as follows: the modeling II. De rest of the study is organized as follows. The modeling of the quadrotor and the control objective are presented in or the quatrotor and the control objective are presented in Section II. Design processes of high-level loop and low-level loop are given in Section III and Section IV, respectively. loop are given in Section III and Section IV, respectively. The rest of the study is organized as follows: the modeling Section II. Design processes of high-level loop and low-level<br>leap are given in Section III and Section IV, respectively. The rest of the study is organized as follows: the modeling of the quadrotor and the control objective are presented in

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Simulation is implemented in Section V to illustrate the effectiveness of the designed controller. This study is finally concluded in Section VI.

## 2. DYNAMIC MODELLING AND CONTROL OBJECTIVES

### 2.1 Dynamic Model of the Quadrotor

The coordinates of the quadrotor system's body frame  ${O<sub>b</sub>, x<sub>b</sub>, y<sub>b</sub>, z<sub>b</sub>}$  centered at the center of gravity (CG) of the quadrotor, the global frame  $\{O_q, x, y, z\}$ , thrusts, moments and gravity are represented in Fig. 1. Using Euler angles  $\varphi \triangleq [\phi, \theta, \psi]^T$  and the rotational matrix  $R \in SO(3)$  from<br>the the body frame to the global frame, and following the Newton-Euler formalism, the dynamic model is derived based on applied forces  $F \in \mathbb{R}^3$  and moment  $M \in \mathbb{R}^3$ (Köksal et al  $(2015)$ ), and is given by

$$
F = RF_b = m\ddot{p} \text{ and } M = J\dot{w} + w \times Jw \qquad (1)
$$

where R is the rotational matrix;  $F_b = [F_{xb}, F_{yb}, F_{zb}]^T =$  $[0, 0, \sum_{i=1}^{4} T_i]^T$  is the applied force vector generated by actuators' thrust forces  $T_i$ ,  $i = 1, 2, 3, 4$ , in the body frame; m is the total mass of the system;  $J_{\varphi} = diag(J_{\phi}, J_{\theta}, J_{\psi})$ is the rotational inertia matrix in the body frame;  $w =$  $[\dot{\phi}, \dot{\theta}, \dot{\psi}]^T$  is the angular velocity of  $O_b$ . (1) leads to the following equations of motion (Koksal et al (2015)):

$$
\ddot{x} = \frac{(T_1 + T_2 + T_3 + T_4)(\sin\psi\sin\phi + \cos\phi\sin\theta\cos\psi)}{m},
$$
  
\n
$$
\ddot{y} = \frac{(T_1 + T_2 + T_3 + T_4)(-\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi)}{m},
$$
  
\n
$$
\ddot{z} = \frac{(T_1 + T_2 + T_3 + T_4)(\cos\phi\cos\theta)}{m} - g,
$$
  
\n
$$
\ddot{\phi} = \frac{l(T_1 - T_2)}{J_\phi} + \frac{(J_\theta - J_\psi)\dot{\psi}\dot{\theta}}{J_\phi} - d_\phi\dot{\phi},
$$
  
\n
$$
\ddot{\theta} = \frac{l(T_3 - T_4)}{J_\phi} + \frac{(J_\psi - J_\phi)\dot{\psi}\dot{\phi}}{J_\phi} - d_\theta\dot{\theta},
$$
\n(2)

$$
\ddot{\psi} = \frac{K_{\psi}(T_1+T_2-T_3-T_4)}{J_{\psi}} + \frac{(J_{\phi}-J_{\theta})\dot{\theta}\dot{\phi}}{J_{\psi}} - d_{\psi}\dot{\psi},
$$

where  $p = [x, y, z]^T$  is the position of  $O_b$ ;  $\varphi \triangleq [\phi, \theta, \psi]^T$ are the Euler angles of rotation;  $\beta = [d_{\phi}, d_{\theta}, d_{\psi}]^T$  are rotational drag parameters;  $T_i$ ,  $i = 1, ., 4$  are thrust forces generated on each actuator;  $l$  is the distance between the center of gravity  $(O_b)$  and each propeller;  $K_{\psi}$  is thrust-tomoment gain; *g* is gravitational acceleration.

Assumption 1. It is assumed that attitude angles are limited as

$$
-\frac{\pi}{2} < \phi < \frac{\pi}{2}, \quad -\frac{\pi}{2} < \theta < \frac{\pi}{2}, \text{ and } -\pi < \psi \leq \pi. \tag{3}
$$

Besides, as an attempt to generate thrust forces using actuators, we use the first-order thrust-input model (Quanser (2013)) in the Laplace domain as follows:

$$
T_i(s) = K \frac{b}{s+b} v_i(s)
$$
\n<sup>(4)</sup>

where  $b$  is the actuator bandwidth;  $K$  is a positive armature gain.

In the control design, we decouple the attitude and the altitude dynamics. Using the control inputs of decoupled dynamics, a PWM input generator is obtained as



Fig. 1. The Qball-X4 quadrotor (Quanser (2013)).

$$
v = Gu = \begin{bmatrix} 0 & 1 & 1 & 1 \\ 0 & -1 & 1 & 1 \\ 1 & 0 & -1 & 1 \\ -1 & 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} u_{\varphi} \\ u_{z} \end{bmatrix},
$$
 (5)

where  $v = [v_1, v_2, v_3, v_4]^T \in \mathbb{R}^4$  is PWM input for each actuator; G is the PWM generator matrix;  $u_{\varphi}$  =  $[u_{\phi}, u_{\theta}, u_{\psi}]^T \in \mathbb{R}^3$  is attitude control inputs;  $u_z \in \mathbb{R}$  is altitude control input. Employing (5) we map the generated control signals  $u = [u_{\varphi}^T, u_z]^T$  to the actual PWM signals v for the four motors.

Similar to (5), we define the effective altitude thrust  $T_z$ and attitude thrusts  $T_{\varphi} = [T_{\phi}, T_{\theta}, T_{\psi}]^T$  as follows:

$$
T_z \triangleq (T_1 + T_2 + T_3 + T_4)/4, \tag{6}
$$

$$
T_{\phi} \triangleq (T_1 - T_2)/2, \tag{7}
$$

$$
T_{\theta} \triangleq (T_3 - T_4)/2, \tag{8}
$$

$$
T_{\psi} \triangleq (T_1 + T_2 - T_3 - T_4)/4. \tag{9}
$$

Combining the nonlinear dynamics (2), thrust-input model  $(4)$  and the relation  $(6)-(9)$ , we derive the nonlinear state variable model as

$$
\dot{X} = F(X, u) = \begin{bmatrix} X_3 \\ X_4 \\ \frac{4}{m} f_1(X_2) X_6 - \zeta \\ A f_2(X_4) + B X_4 + \Gamma X_5 \\ -b X_5 + K b u_{\varphi} \\ -b X_6 + K b u_z \end{bmatrix}, \quad (10)
$$

with state vector

$$
X = [X_1, X_2, X_3, X_4, X_5, X_6]^T \in \mathbb{R}^{16},
$$
 (11)

where  $X_1 = p = [p_l^T, p_z]^T, X_2 = \varphi \triangleq [\phi, \theta, \psi]^T, X_3 =$  $\dot{X}_1 = v, X_4 = \dot{X}_2 = w_\varphi, X_5 = T_\varphi \triangleq [T_\phi, T_\theta, T_\psi]^T$ are 3-D vectors;  $X_6 = T_z$ ;  $\zeta = [0, 0, g]^T$ ;  $f_1(X_2) =$  $\int \cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi$  $\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi$ <br> $\sin \phi \cos \theta$ <sup>1</sup> ;  $f_2(X_4) =$  $\sqrt{ }$  $\perp$  $\dot{\theta}\dot{\psi}$  $\dot{\phi}\dot{\psi}$  $\dot{\phi}\dot{\theta}$ <sup>1</sup>  $\big|$ ;  $A =$  $diag(\frac{J_{\theta}-J_{\psi}}{J_{\phi}},\frac{J_{\psi}-J_{\phi}}{J_{\theta}},\frac{J_{\phi}-J_{\theta}}{J_{\psi}});~~B~~=~~diag(-d_{\phi},-d_{\theta},-d_{\psi})$  $\Gamma = diag(\frac{2l}{J_{\phi}}, \frac{2l}{J_{\theta}}, \frac{4K_{\psi}}{J_{\psi}}).$ 

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