Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Disturbance observer based hierarchical control of coaxial-rotor UAV

M.Rida Mokhtari [a,b,*], Brahim Cherki [a,b], Amal Choukchou Braham [b]

[a] École supérieure des sciences appliquées de Tlemcen, Algeria
[b] Laboratoire d'Automatique de Tlemcen (LAT). Electrical Engineering Department, Tlemcen University, Algeria

ARTICLE INFO

Article history:
Received 16 May 2016
Received in revised form
16 November 2016
Accepted 6 January 2017

Keywords:
Disturbance Observer
Finite time convergence
Hierarchical control
Coaxial-rotor

ABSTRACT

This paper propose an hierarchical controller based on a new disturbance observer with finite time convergence (FTDO) to solve the path tracking of a small coaxial-rotor-typs Unmanned Aerial Vehicles (UAVs) despite of unknown aerodynamic efforts. The hierarchical control technique is used to separate the flight control problem into an inner loop that controls attitude and an outer loop that controls the thrust force acting on the vehicle. The new disturbance observer with finite time convergence is intergated to online estimate the unknown uncertainties and disturbances and to actively compensate them in finite time.The analysis further extends to the design of a control law that takes the disturbance estimation procedure into account. Numerical simulations are carried out to demonstrate the efficiency of the proposed control strategy.

1. Introduction

Unmanned aerial vehicles (UAVs) are promising to achieve many useful applications in both civil and military scenarios. The development of such systems pose a number of problems in sensing and control. We are particularly interested in controlling the coaxial rotor, a helicopter having two main rotors driven by two brushless DC motors rotating in opposite direction in order to overcome gyroscopic torque and cancel the drag torque produced by each rotor. The altitude is regulated by increasing or decreasing the thrust of both rotors. This helicopter uses a mechanical device known as a swashplate (collective pitch) driven by two servo motors placed on the lower rotor to change the pitch and roll angle incidence to obtain the pitch and roll control torques of the vehicle [24]. The yaw torque is ensured by a differential speed variation between the two rotors. A coaxial rotor is controlled by varying the angular speed of each rotor and the swashplate angle incidence of the lower rotor [2,3]. The force produced by each motor is proportional to the square of the angular speed. The coaxial system is under-actuated with only the 1-degree-of-freedom (DOF) thrust force input for the 3- dimensional Cartesian dynamics, although the rotational dynamics in SO(3) is fully-actuated.

Numerous strong control techniques have been proposed for the control of coaxial-rotor or similar systems. Many works focus on linear controllers have been developed to achieve flight performances of rotorcraft configurations like PD controller [5] and PID controller [6]. More recently, interest has been focused on nonlinear control laws like adaptive backstepping control in [7,8], nonlinear PID controller in [9], an integral predictive controller H_∞ [10], the control via singular perturbations [11]. In [12] an experimental vision regulation was applied to the quadrotor systems. A sliding mode controllers was presented in [2,13], a disturbance observer based control was applied in [14,15] and an extended state observer based control was applied to coaxial-rotor in [1,16].

Backstepping is a well known technique extensively used to control the nonlinear systems [1]. However, in the presence of model uncertainties and disturbances, this algorithm can not guarantee the stability of the closed loop system and the asymptotic convergence of the tracking error. Several methodologies can be combined with backstepping to attain desirable characteristics of a control law, such as robustness to external disturbances and actuation boundedness. The first one known as adaptive backstepping method [17], which is able to reject the disturbance, once its estimation is available or measured. The second is called robust backstepping method [4], which is able to reject the disturbance, without needing information on its evolution. In general, the backstepping control technique can not applicable directly to control the underactuated RUAVs system.

The backstepping methodology for helicopters is constructed by taking into acount a dynamic extension of the thrust actuation, and hence, the control equations becomes complex and difficult to implement. A common characteristic unifies these controller: the

* Corresponding author at: École supérieure des sciences appliquées de Tlemcen, Algeria.
E-mail addresses: mokhtari_rida_aut@hotmail.fr (M.Rid. Mokhtari), b.cherki@gmail.com (B. Cherki), amel_choukchou@yahoo.fr (A.C. Braham).

http://dx.doi.org/10.1016/j.isatra.2017.01.020

existence of a singularity in the control law for zero thrust.Typically, the singular condition is either ignored or the control laws are modified when near the singularity, but that leads to a loss of the stability properties and can endanger a vehicle unnecessarily.

In this paper, we propose an original control algorithm based on hierarchical backstepping control driven by a finite time disturbance observer to solve the path tracking control of a small coaxial rotor vehicle subject to unknown uncertainties and aerodynamic disturbances. The hierarchical flight control is proposed to separate the flight control problem into high level position control and a low level attitude control. The question of modeling the aerodynamic effects is over thrown by considering them as unknown perturbations that act on the system. To address the issues of uncertainties and external disturbances, a new disturbance observer is designed to online estimate the unknown uncertainties and disturbances and to actively compensate them in in finite time. The finite-time sliding mode control [18-20] and observer disturbance [21-23] are used to construct the presented disturbance observer. The proposed FTDO offers superior faster convergence, better disturbance rejection capability and robustness against the model uncertainties and disturbances. The aim of control action is to enhance the performance of hierarchical control working in the outer control loop with the observer operating in the inner perturbation reconstruction-rejection loop. The performance for closed-loop system can be recovered if the total uncertainty/disturbance is timely compensated via disturbance observer.

The rest of paper is organized as follows. Section 2 presents the dynamical model of the coaxial-rotor UAV. Our proposed control algorithm based on hierarchical backstepping intergrated with a new disturbance observer for coaxial rotors is then presented and detailed in Section 3. Simulation results are then presented in Section 4 and conclution is given in Section 5.

2. Vehicle dynamics modeling

We describe in this section the dynamical model of a small coaxial-rotor UAV which represent the behavior of the real system over time. This system is an underactuated mechanical system with six degrees of freedom, and only four degrees of freedom controlled with four control inputs, the thrust T_z produced by the two rotors and the control torque $\Gamma_a = (\tau_\phi, \tau_\theta, \tau_\psi)^T$ produced by both rotors and Swash-plate incidence angles. The main thrust is used to compensate the gravity force and to control the vertical movement [3]. The horizontal movements are controlled by directing the force vector in the appropriate direction (thrust vectoring control) through the cyclic swash plate. Control moments are used to control the aircraft body orientation which controls the rotor-craft horizontal movement.

Consider the coaxial-rotor as a solid body evolving in a 3D space and subject to the main thrust and three torques [1,24] as depicted in Fig. 1. Let $\mathcal{B}{:=}(G, x_b, y_b, z_b)$ the body-fixed frame attached to the center of gravity of the aerial vehicle, where x_b is the longitudinal axis, y_b is the lateral axis and z_b is the vertical direction in hover conditions and $\mathcal{I}{:=}(O, x_I, y_I, z_I)$ is the Earth frame. The generalized coordinates describing the rotorcraft position and orientation are $q = [\xi, \eta]^T$, where $\xi = (x, y, z)^T \in \mathbb{R}^3$ represents the translation coordinates relative to the inertial frame and $\eta = (\phi, \theta, \psi)^T \in \mathbb{R}^3$ are the classic yaw, pitch and roll Euler angles commonly used in aerodynamic applications. The rotation matrix $R_\eta = R_\psi R_\theta R_\phi \in SO(3)$ is the rotation matrix between Earth and body coordinate systems given by [25][1]

[1] The abbreviations $s_\star$ and $c_\star$ denote $\sin(\star)$ and $\cos(\star)$, respectively.

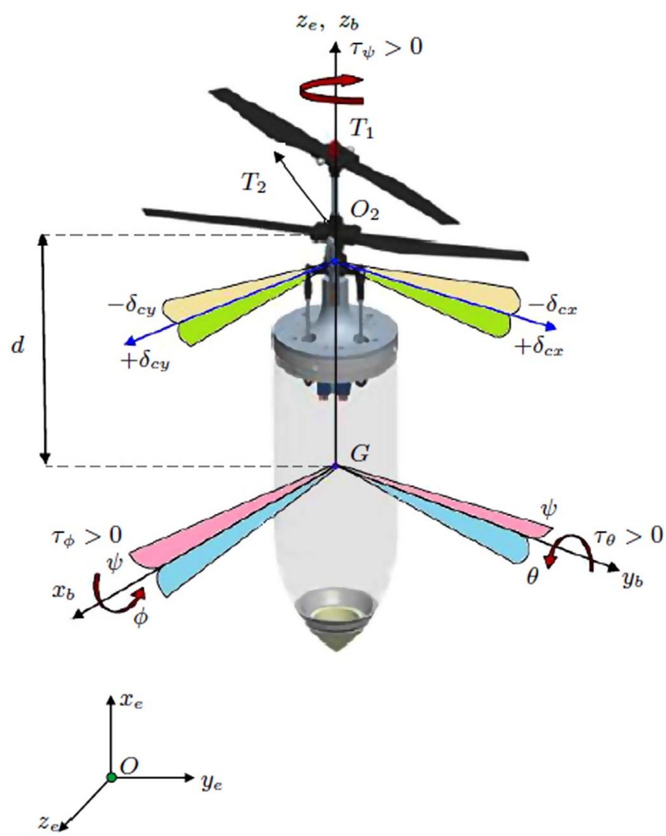

Fig. 1. Diagram showing the reference frame and forces of the coaxial-rotor UAV flight.

$$R_\eta = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{pmatrix}$$

The dynamic model of the coaxial-rotor helicopter is expressed using Newton-Euler formulation [1,24]

$$\begin{cases} m\ddot{\xi} &= R_\eta T - mgz_e + F_{ext} \\ \mathbb{J}\ddot{\eta} &= \Gamma_a - C(\eta, \dot{\eta})\dot{\eta} + \Gamma_{ext} \end{cases} \tag{1}$$

where $\mathbb{J} = J\Psi(\eta) \in \mathbb{R}^{3\times3}$ is an auxiliary positive inertia matrix provided that $(\theta \neq k\pi/2)$, $m \in \mathbb{R}$ specifies the mass, $J \in \mathbb{R}^{3\times3}$ is the diagonal inertia matrix, g the acceleration due to a gravity and $C(\eta, \dot{\eta})\dot{\eta}$ is given by

$$C(\eta, \dot{\eta}) = \dot{\mathbb{J}}\dot{\eta} - sk(\Psi\dot{\eta})\mathbb{J}\dot{\eta}$$

The attitude kinematic matrix $\Psi(\eta) \in \mathbb{R}^{3\times3}$ and the skew anti-symmetric matrix $sk(\beta)$ of β are defined, respectively, as [18]

$$\Psi(\eta) = \begin{pmatrix} 1 & 0 & -s_\theta \\ 0 & c_\phi & s_\phi c_\theta \\ 0 & -s_\phi & c_\phi c_\theta \end{pmatrix}; \quad sk(\beta) = \begin{pmatrix} 0 & -\beta_3 & \beta_2 \\ \beta_3 & 0 & -\beta_1 \\ -\beta_2 & \beta_1 & 0 \end{pmatrix}$$

2.1. Forces acting on the vehicle

The thrust vector generated by the two rotors is a function of the rotor angular speed and the cyclic tilt angles. The upper rotor has no swashplate, then, produces only the vertical thrust, whereas the lower rotor generates both a vertical thrust and lateral forces due to the swashplate incidence angles. Then, the total thrust vector T is defined [24]

Please cite this article as: Mokhtari MRida, et al. Disturbance observer based hierarchical control of coaxial-rotor UAV. ISA Transactions (2017), http://dx.doi.org/10.1016/j.isatra.2017.01.020