ISA Transactions 56 (2015) 86–101

Contents lists available at ScienceDirect

ISA Transactions

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

A new robust control for minirotorcraft unmanned aerial vehicles

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ARTICLE INFO

Article history:
Received 23 October 2014
Received in revised form
5 December 2014
Accepted 19 December 2014
Available online 9 February 2015
This paper was recommended for publication by Dr. Jeff Pieper.

Keywords:
Backstepping
Finite-time stability
Quadrotor
Robust control
Rotocraft UAV

ABSTRACT

This paper presents a new robust control based on finite-time Lyapunov stability controller and proved with backstepping method for the position and the attitude of a small rotorcraft unmanned aerial vehicle subjected to bounded uncertainties and disturbances. The dynamical motion equations are obtained by the Newton–Euler formalism. The proposed controller combines the advantage of the backstepping approach with finite-time convergence techniques to generate a control laws to guarantee the faster convergence of the state variables to their desired values in short time and compensate for the bounded disturbances. A formal proof of the closed-loop stability and finite-time convergence of tracking errors is derived using the Lyapunov function technique. Simulation results are presented to corroborate the effectiveness and the robustness of the proposed control method.

1. Introduction

The growing interest for the robotics research community in rotary wing unmanned aerial vehicles (RUAVs) and unmanned micro air vehicles (UMAVs) as exemplified by helicopters [1,7,14] and multi-rotors [1–3,6,4,5,8,7,9] is partly due to the specific applications in both civil and military scenarios that can be addressed with such systems like surveillance, building exploration, information collection, aggressive maneuvers in confined and obstructed environments. The development of the small rotorcraft are motivated by a crucial characteristics such as small size, autonomous navigation capacity, low cost, the capability of vertical takeoff and landing (VTOL), abilities to hover, omnidirectional flight, flight at very low altitudes and high maneuverability. Current research goals include the development of specialized unmanned air vehicles capable of performing hover as well as forward flight and aggressive flight with high speeds and accelerations to reach remote areas. Several designs of small rotorcraft are available according to the number of rotors and their mechanisms. Some have two rotors (Gun Launched MAV [4] or the classical helicopter [1,14]). Another have three rotors (Trirotor [8] and Tri-TiltRotor [9]). For the four rotors, we find the quadrotor [3,6] and the Quad-Tilt-Wing (QTW) [1]. To achieve a good tracking performance and guarantee the autonomous operation capabilities, the development of simple, robust and intelligent control laws for stabilizing and controlling the RUAVs/UMAVs becomes more and more important.

Most rotary-wing aerial vehicles are underactuated mechanical systems moving with six degrees of freedom but only four degrees of freedom can be controlled independently with four control inputs, which generally include 1-DOF thrust force input and the 3-DOF angular velocity input. The main force is used to compensate the gravity force and to control the vertical movement. The horizontal movements are controlled by directing the force vector in the appropriate direction (thrust vectoring control). The control moments are thus used to control the aircraft body orientation which controls the rotorcraft horizontal movement.

In the relevant literature, many works have been done on the modeling, navigation and on the flight control designs for a small rotorcraft. The modeling is essential for designing a good controller (Chriette et al. [7], Lozano et al. [5,8], Hamel et al. [12], Bouabdallah et al. [11], etc.) Many works based on the linear/nonlinear controllers have been developed to meet the increasing demands on the RUAVs/UMAVs. Then, many linear control techniques such as the application of (PID and LQ) controllers to the rotorcraft UAV were presented in [11]. In [15] Tayebi and McGilvray present a PD^2controller, which had the exponential convergence property. But in those linear techniques, the proof of convergence is not guaranteed when the vehicle moves away from its flight domain and the control approaches have limited capability to alleviate the coupling among variables. To overcome some of the limitations and drawbacks of the linear approach, a variety of nonlinear flight control techniques have also been

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http://dx.doi.org/10.1016/j.isatra.2014.12.003
0019-0578/

developed. Among these: the control with bounded inputs [5,8], integral predictive/nonlinear H_∞ [17] and backstepping technique [4,13,14]. But very few works have been made on the influence of uncertainties/disturbances on the flying system [10]. However, the presence of uncertainties/disturbances as wind gusts and payload limits the performance and robustness of the control.

The backstepping method [14,18–22] is a recursive method based on Lyapunov theory to design control algorithm for stabilizing the nonlinear systems and ensure the asymptotic convergence of tracking error. However, in the presence of model uncertainties and disturbances, the conventional backstepping method cannot guarantee the stability of the closed-loop system and the convergence speed of the tracking error. Sliding mode control (SMC) [16,29,30] is one of the important approaches to handle nonlinear systems with uncertainties and bounded external disturbances. The first step in the SMC design is to choose a sliding manifold, so that the state variables restricted to the manifold have a desired dynamics. Their main advantages are the attractive characteristics with the asymptotic convergence of tracking errors, robustness properties and simplicity in implementation. However, the major drawback of SMC in practical applications is undesired chattering due to high frequency switching which consists in large oscillations in the neighbourhood of the sliding variable and the errors dynamics cannot converge to zero in finite-time. Obviously, it is more desirable to use the finite-time control [25–27]. Compared with SMC, the finite-time controller offers superior properties such as faster convergence, higher-precision control, better disturbance rejection capability and robustness against the model uncertainties and disturbances. In order to enhance convergence speed and achieve finite-time convergence, a solution is to combine the backstepping design approach with finite-time stability control.

The main contribution of this paper consists in proposing a robust finite-time control approach for the position and the attitude tracking problem of a small rotorcraft generally and the quadrotor MAV in particular in the presence of disturbances that include external wind gusts, internal couplings and unmodelled dynamics. The proposed control method is designed by integrating the backstepping technique with the finite-time control approach to generate a control laws to guarantee the finite-time stability and guarantee the finite-time reachability to a boundary layer in the presence of perturbation and external disturbance. The basic of the proposed controller is to combine the advantages of the backstepping design method with extra nonlinear correction terms to achieve a high performance and robustness against the bounded disturbances/uncertainties and ensure the finite-time convergence of tracking error to a small neighbourhood of the origin. The linear correction terms have a better convergence performance when far away from the equilibrium, that makes the system exponentially converges to the origin, whereas the nonlinear correction terms makes the trajectories of the system converge in finite-time. The Lyapunov function obtained for the closed-loop system is used to analyze the performance of the proposed control in tracking an arbitrary trajectory. The idea of controlling the rotorcraft position through its orientation is to separate the structure model into three subsystems. The control strategy is motivated by several reasons, the rotorcraft UAVs are underactuated mechanical systems, the obtained flight controllers are coupled and difficult to implement. This architecture reduces the complexity of the control signals and the obtained control laws are easy to implement and to tune.

Then, the results displayed in this paper are original for several reasons:

- The control strategy is designed to solve the path tracking problem, which is divided in the respective problem, for three subsystems: altitude S_1, latitudinal and longitudinal S_2, and heading control S_3 as shown in Fig. 2.
- A new robust controller based on the backstepping method with finite-time Lyapunov stability controller for the position and the orientation of a small rotorcraft and successfully applied to a quadrotor MAV.
- The convergence of the tracking error in finite-time to a small neighbourhood of the origin and the stability of the closed-loop system is formally established.

The paper is organized as follows. In Section 2 the detailed mathematical model of a rotorcraft MAV is presented while in Section 3 the proposed nonlinear control is designed based on robust finite-time control approach and proved by backstepping design method applied to a small quadrotor system. Section 4 contains the main results of the paper and presents the analysis of the closed-loop performance of the proposed control. In Section 5, some simulations are carried out to show the behavior and stability of the closed-loop system. Conclusions are drawn in Section 6.

2. Rotorcraft dynamic model

The mathematical model for small rotorcraft is essential for designing a good controller. In most cases this model is obtained by representing the aircraft as a rigid body evolving in a three dimensional space. Let $\mathcal{B} := (x_b, y_b, z_b)$ be the coordination body-fixed reference frame (BFF) where x_b is the longitudinal axis, y_b is the lateral axis and z_b is the vertical direction in hover conditions and $\mathcal{I} := (x_e, y_e, z_e)$ be the Flat-Earth model inertial reference frame (EFF) as depicted in Fig. 1. The generalized coordinates describing the rotorcraft position and orientation are $q^T = (\xi, \eta)$, the vector $\xi^T = (x, y, z)$ are the rotorcraft position in the frame $\mathcal{I}$ and $\eta^T = (\phi, \theta, \psi)$ are the three Euler angles representing the orientation of the rotorcraft in frame $\mathcal{I}$, where ϕ is the roll angle around the x-axis, θ is the pitch angle around the y-axis, and ψ is the yaw angle around the z-axis. The rotation matrix $R_\eta := R_\psi R_\theta R_\phi \in SO(3)$ representing the orientation of the airframe relative to a fixed inertial frame expressed as follows[2]:

$$R_\eta = \begin{pmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\phi s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{pmatrix} \tag{1}$$

The equation of motion for a rotorcraft UAV such as the quadrotor helicopter are given by the following Newton–Euler equation [1,6,7]:

$$\begin{aligned} \sum\nolimits_T : \begin{pmatrix} \dot{\xi} \\ m\dot{v} \end{pmatrix} &= \begin{pmatrix} v \\ R_\eta [F_p - F_g] + F_e \end{pmatrix} \\ \sum\nolimits_R : \begin{pmatrix} \dot{R}_\eta \\ J\dot{\Omega} \end{pmatrix} &= \begin{pmatrix} R_\eta sk(\Omega) \\ -\Omega \times J\Omega + \tau + M_e \end{pmatrix} \end{aligned} \tag{2}$$

where $v^T = (\dot{x}, \dot{y}, \dot{z})$ and $\Omega^T = (p, q, r)$ are, respectively, the linear and angular velocities of the rotorcraft such that $v \in \mathcal{I}$ and $\Omega \in \mathcal{B}$. $m \in \mathbb{R}$ represents the total mass of the aircraft, $sk(\Omega)$ the skew symmetric matrix induced by Ω and $J \in \mathbb{R}^{3\times3}$ the inertia matrix around the centre of mass expressed in frame $\mathcal{B}$.

The translational forces combine gravity, main thrust and other body force components (wind gusts, payload, mechanical failure etc.). F_p and $F_g = mR_\eta^T G$ are the main force generated by the rotors and the gravity effect force affecting the rotorcraft body with $G^T = [0, 0, 9.81]\ \mathrm{m/s^2}$. The rotational torques include the main

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