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Unmanned Aerial Vehicles parameter estimation using Artificial Neural Networks and Iterative Bi-Section Shooting method

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ABSTRACT

Quadrotor Unmanned Aerial Vehicles (UAVs) can perform numerous tasks fearless of unnecessary loss of human life. Lately, to enhance UAV control performance, system identification and states estimation has been an active field of research. This work presents a simulation study that investigates unknown dynamics model parameters estimation of a Quadrotor UAV under presence of noisy feedback signals. The latter constitute a challenge for UAV control performance especially with the presence of uncertainties. Therefore, estimation techniques are usually used to reduce the effect of such uncertainties. In this paper, three estimation methods are presented to estimate unknown parameters of the "OS4" Quadrotor. Those methods are Iterative Bi-Section Shooting method "IBSS", Artificial Neural Network method "ANN", and "Hybrid ANN_IBSS", which is a novel method that integrates ANN with IBSS. The "Hybrid ANN_IBSS" is the main contribution of this work.

Percentage error of the estimated parameters is used to evaluate accuracy of the aforementioned methods. Results show that IBSS and ANN are capable of estimating most of the parameters even with the presence of noisy feedback signals. However, their performance lacks accuracy when estimating small-value parameters. On the other hand, Hybrid ANN_IBSS achieved higher estimation accuracy compared to the other two methods. Accurate parameter estimation is expected to enhance reliability of the "OS4" dynamics model and hence improve control quality.

1. Introduction

UAVs have garnered a great deal of interest from a number of scholars and organizations in the past few years. They have been broadly used in surveillance, tracking, navigation, communication, civilians and military applications. However, autonomous control of UAVs is a very challenging task. UAVs generally possess highly nonlinear dynamics models. In addition, they represent six DOF flying rigid bodies, which are influenced by wind gusts disturbances during flight or external thrust forces associated with complex rotor dynamics. Moreover, fuel consumption or unexpected loss of some parts cause modeling uncertainties.

Quadrotor UAVs offer a great tool to verify several control techniques; which justifies the recent attention by research community. Raffo et al. [1] used predictive nonlinear control strategy to achieve robust Quadrotor trajectory tracking. Similar studies were investigated by Cabecinhas et al. [2] and Guadarrama-Olvera et al. [3]. Bou-Ammar presented a comparison study between two Quadrotor autopilots tasked to maintain a desired velocity vector. Results indicated that quality performance required detailed control engineering awareness [4]. Recently, Sanna et al. [5,6] used Kinect-based interface to control the Ar. Drone Quadrotor.

Sliding mode control was investigated in Ref. [7–9] in order to overcome UAVs modeling uncertainties. Zeghlache et al. [10] proposed Fuzzy logic to eliminate the chattering effect associated with sliding mode control of a Quadrotor UAV. In addition, Zheng introduced a novel robust terminal sliding mode control (NRTSMC), and an under-actuated system sliding mode control (USSMC) to overcome the strong coupling and under-actuated problems of a small Quadrotor [11].

Performance of UAVs control systems introduced above, depend on accuracy of feedback measurement and reliability of dynamics model. For instance, high noise-to-feedback ratios might cause UAVs actual path to deviate from the desired one. Reliable dynamics

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Nomenclature

p	roll angular rate in earth frame
q	pitch angular rate in earth frame
r	yaw angular rate in earth frame
ϕ	roll angle in body frame
θ	pitch angle in body frame
ψ	yaw angle in body frame
x	position along x axis
y	position along y axis
z	position along z axis
$s\phi$	$\sin\phi$
$c\phi$	$\cos\phi$
$s\theta$	$\sin\theta$
$c\theta$	$\cos\theta$
$s\psi$	$\sin\psi$
$c\psi$	$\cos\psi$
T	sample time
$\omega 1, \ldots 4$	rotor speed
δ	input torque
U_c	thrust force input

model requires accurate parameter estimation using high quality feedback signals.

Therefore, there has been an increased interest in system identification and states estimation of UAVs. For example, many studies were conducted on Quadrotor state-estimation [12–16]. Nobahari used the Continuous Ant-Colony filter (CACF) in order to estimate the vertical velocity of Quadrotor UAV during landing procedure [17]. Nicol et al. applied Cerebellar Model Arithmetic Computer (CMAC) nonlinear approximator to update the changing parameters of a prototype helicopter. CMAC provided quick accurate yet computation-efficient approximations [18]. Stanculeanu used a black box system identification based Prediction Error Method (PEM) to estimate the parameters of Quadrotor dynamics model [19]. While, Falkenberg used a Gray-Box-based, iterative parameter identification approach, that offered good accuracy [20]. Al-Shabi et al. [21] introduced a comparison study between two parameter estimation methods; recursive least squares (RLS) and Smooth Variable Structure Filter (SVSF) applied over an “OS4” Quadrotor model. Results indicated that both RLS and SVSF have good performance, rapid convergence, and low percentage error with the absence of introduced state noise. However, SVSF showed superior performance with the presence of additive noise and uncertainties.

This work aims to estimate the unknown parameters of the “OS4” Quadrotor [22] to attain a reliable dynamics model and enhance control quality. The following section presents the continuous dynamics model of the “OS4” Quadrotor. The section also presents the derivation of the discrete time model. The derived discrete time model is then used to simulate flight trajectories based on predefined input signal, assuming known model parameters. The subsequent sections estimate the unknown parameters of the considered Quadrotor using three estimation methods with noisy versions of the simulated trajectories. Section 3 presents “The Iterative Bi-Section Shooting (IBSS)”. Section 4 presents “The Artificial Neural Network (ANN)”. Section 5 presents the main contribution of this work “the Hybrid ANN and IBSS method”. Results and conclusions are discussed in Sections 6 and 7, respectively.

2. Quadrotor dynamics model

Quadrotor UAVs consists of four rotors in a cross configuration. Each rotor produces an upward thrust against its own weight. Fig. 1 shows the (x, y, z) frame attached to the body $\boldsymbol{B}$ of a Quadrotor.

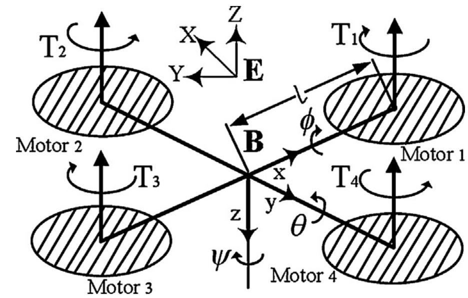

Fig. 1. Schematic diagram of a Quadrotor [21].

The frame defines the Euler angles pitch, roll, and yaw (φ, θ, ψ), respectively, of the UAV. The fixed (X, Y, Z) Earth frame $\boldsymbol{E}$ is used to define the global position and orientation of the flying vehicle.

The general dynamics model of Quadrotor UAVs is discussed in Refs. [1,2,23]. State-of-the-art work is to find an efficient Quadrotor mathematical model. The dynamics model is then linearized to apply linear control theory. A general dynamics model for Quadrotor UAV is described by Eqs. ((1)–(13)) [24].

This model is selected as a benchmark for this work.

$$\dot{p} = qr\alpha_1 - \alpha_2 q + \alpha_3 \delta_{roll} \tag{1}$$

$$\dot{q} = pr\alpha_4 + r\alpha_5 + \alpha_6 \delta_{pitch} \tag{2}$$

$$\dot{r} = pq\alpha_7 + \alpha_8 \delta_{yaw} \tag{3}$$

$$\dot{\phi} = p + \tan\theta(qs\phi + rc\phi) \tag{4}$$

$$\dot{\theta} = qc\phi - rs\phi \tag{5}$$

$$\dot{\psi} = (qs\phi + rc\phi)\sec\theta \tag{6}$$

$$\ddot{x} = (s\phi c\psi - s\psi s\theta c\phi)\frac{u_c}{m} \tag{7}$$

$$\ddot{y} = (-s\psi s\phi - s\theta c\phi c\psi)\frac{u_c}{m} \tag{8}$$

$$\ddot{z} = -g + (c\theta c\phi)\frac{u_c}{m} \tag{9}$$

$$\delta_{roll} = Lb(\omega_4^2 - \omega_2^2) \tag{10}$$

$$\delta_{pitch} = Lb(\omega_3^2 - \omega_1^2) \tag{11}$$

$$\delta_{yaw} = d(\omega_4^2 + \omega_2^2 - \omega_3^2 - \omega_1^2) \tag{12}$$

$$uc = b(\omega_4^2 + \omega_2^2 + \omega_3^2 + \omega_1^2) \tag{13}$$

α_1 to α_8 are the Quadrotor model parameters, where,

$$\alpha_1 = \frac{I_y - I_z}{I_x}, \alpha_2 = \frac{J_R d}{I_x}, \alpha_3 = \frac{1}{I_x}, \alpha_4 = \frac{I_z - I_x}{I_y},$$

$$\alpha_5 = \frac{J_R d}{I_y}, \alpha_6 = \frac{1}{I_y}, \alpha_7 = \frac{I_x - I_y}{I_z}, \alpha_8 = \frac{1}{I_z}$$

Moreover, $(p, q$ and $r)$ are pitch, role, and yaw angular velocities measured in the fixed frame, respectively. Eqs. ((10)–(12)) define the relation between rotor speed ω_i and torque needed to change Euler angles. The total thrust force uc is given by Eq. (13). Table 1 defines the rest of parameters. Details of the previous model can be found in Ref. [24].

In order to apply parameter estimation a discrete time model needs to be developed using the presented dynamics model. For that, the state variable vector $\mathbf{X}$ is defined as shown in Eq. (14), then its derivative $\dot{\mathbf{X}}$ can be obtained as shown in Eqs. ((15)–(17)).

$$\mathbf{X} = [x_1\, x_2\, x_3\, x_4\, x_5\, x_6\, x_7\, x_8\, x_9\, x_{10}\, x_{11}\, x_{12}]^T$$
$$\mathbf{X} = \left[x\, \dot{x}\, y\, \dot{y}\, z\, \dot{z}\, \phi\, p\, \theta\, q\, \psi\, r\right]^T \tag{14}$$