Mechanical Systems and Signal Processing ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

# An adaptive trajectory tracking control of four rotor hover vehicle using extended normalized radial basis function network

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ARTICLE INFO

*Article history:*
Received 16 January 2016
Received in revised form
5 May 2016
Accepted 31 May 2016

*Keywords:*
Adaptive neural network control
Extended normalized radial basis function
Four rotor hover vehicle
Unmodeled dynamics approximation

ABSTRACT

In this paper, an adaptive trajectory tracking controller based on extended normalized radial basis function network (ENRBFN) is proposed for 3-degree-of-freedom four rotor hover vehicle subjected to external disturbance i.e. wind turbulence. Mathematical model of four rotor hover system is developed using equations of motions and a new computational intelligence based technique ENRBFN is introduced to approximate the unmodeled dynamics of the hover vehicle. The adaptive controller based on the Lyapunov stability approach is designed to achieve tracking of the desired attitude angles of four rotor hover vehicle in the presence of wind turbulence. The adaptive weight update based on the Levenberg-Marquardt algorithm is used to avoid weight drift in case the system is exposed to external disturbances. The closed-loop system stability is also analyzed using Lyapunov stability theory. Simulations and experimental results are included to validate the effectiveness of the proposed control scheme.



## 1. Introduction

During past one decade, a considerable increase has been observed in the usage of multirotor unmanned air vehicles (MUAV) in various civil and military applications. In contrast to the conventional UAV systems MUAV(s) are cost effective and offer simple mechanical construction, vertical takeoff and landing (VTOL), hover capability, and enhanced maneuverability to operate in the Cartesian space [1]. Various control schemes have been devised and applied so far for different configurations of MUAV in variable operating conditions including four rotor hover vehicle, quadrotor, and hexarotor among many. However, MUAV control is still a challenging task because of the nonlinearities, highly coupled system dynamics and MUAV operation in the presence of wind disturbances.

Conventional control techniques including PID, LQR, $H_\infty$ controllers have been used for MUAV control by researchers so far (e.g. [2–12]). The aforementioned conventional control techniques perform well in ideal conditions. However, nonlinearities and complexities in the system make it prone to modeling inaccuracies or unmodeled dynamics. The

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http://dx.doi.org/10.1016/j.ymssp.2016.05.043
0888-3270/

Please cite this article as: R. ul Amin, et al., An adaptive trajectory tracking control of four rotor hover vehicle using extended normalized radial basis function network, Mech. Syst. Signal Process. (2016), http://dx.doi.org/10.1016/j.ymssp.2016.05.043

abovementioned control techniques are all based on a linearized model; hence are not practically effective for the system that deviates from its operating regime. Therefore, it can be concluded that the usage of conventional control techniques hinder satisfactory tracking performance in the presence of external disturbances.

Adaptive control technique has been found highly effective as compared to other control methods in many applications (e.g. in [13–16]), especially to handle unmodeled dynamics and parametric uncertainties. Literature shows that in past few years a number of adaptive control based techniques have been used for 3 degree-of-freedom (3-DOF) hover vehicle and 6-DOF quadrotor MUAV (e.g. [17–20]). Huang and colleagues proposed backstepping based adaptive controller for tracking control of quadrotor subjected to mass uncertainty [17]. Model reference adaptive controller (MRAC) was used for actuator uncertainties of quadrotor and adaptive controller was also compared with linear controller [18]. Sadeghzadeh et al. proposed MRAC and Gain-scheduled PID controllers for quadrotor under fault conditions [19]. Diao et al. presented nonlinear adaptive controller for quadrotor having uncertainties in dynamic model [20]. Direct-approximate adaptive control based on Cerebellar Model Arithmetic Computer (CMAC) was presented in [21] for quadrotor with unknown payload and was being subjected to disturbance. In [22], Fang used adaptive integral backstepping control for micro quadrotor subjected to disturbance and also varying mass. Bouadi [23] proposed adaptive sliding mode controller for stabilization and tracking of quadrotor attitude and altitude with parametric uncertainties and disturbances. Command filtered backstepping adaptive controller was presented in [24] for a quadrotor in the presence of external disturbance and model uncertainties. A nonlinear adaptive controller was proposed in [25] for quadrotor tracking and disturbance rejection control in the presence of model uncertainties. Chen et al. [26] presented an adaptive compensation control for 3DOF hover vehicle using disturbance observe and quantum information for external disturbance and unknown actuator failure problems. Yang et al. proposed adaptive fuzzy sliding mode based controller for trajectory tracking control with uncertain actuator faults [27]. A reconfigurable control scheme using quantum logic and simple adaptive control was proposed in [28] for tracking control of quadrotor subjected to faults in propellers. Islam and colleagues proposed adaptive controller to address the tracking problem of quadrotor in the presence of modeling error and disturbance uncertainty [29]. Recently, Chen and colleagues addressed the trajectory tracking control problem of quadrotor with unknown parameters and proposed a fault-tolerant control scheme using sliding mode fault observer [30]. Summarizing the literature study, it shows that a significant amount of work has been done for the control of different configurations of MUAV subjected to external disturbances, parameter uncertainties, and actuators fault. However, a serious need has been felt to address the issue of the unmodeled dynamics approximation which may introduce instability in the system and cause intermittent problem in steady state response [31].

Computational intelligence techniques such as fuzzy logic, neural network and Neuro-fuzzy systems are becoming increasingly popular in control applications (e.g. [32–34]). The computational intelligence techniques not only handle modeling inaccuracies but also effectively solve implementation issues such as packet dropouts, and quantization errors, among may (e.g. [35–39]). Several computational intelligence approaches have been successfully implemented for dynamics estimations and unmodeled dynamics approximation in control applications (e.g. [40–43]). However, neural network based dynamics estimation has been proved effective in many mechanical systems applications (e.g. [44–46]) as compared to the rest. Literature analysis revealed that till date there is no neural network based adaptive controller used for attitude control problem of four rotor hover vehicle and MUAV, except [21] in which CMAC is used for nonlinear function approximation. However, CMAC based control suffers from deviation in states' error called *bursting* when subjected to sinusoidal disturbances and subsequently can make system unstable [47]. RBF networks have also been employed in several robotic manipulator control applications for nonlinear function approximation (e.g. [36,39,40]). A typical RBF approximates a function by providing a unique solution for a specific input data set. Although, this "unique solvability" feature is cited as a potential advantage of RBF [48], but it does not provide flexibility to incorporate design requirements and capability to handle uncertainties[49].

In this paper a new Neuro-adaptive controller is proposed to address trajectory tracking problem of four rotor hover vehicle using extended normalized RBF network (ENRBFN) to approximate unmodeled dynamics of the systems. An ENRBFN combines the features of normalized RBF [50] and E-RBF [49] and offers excellent input noise tolerance, disturbance rejection, uncertainty handling, and fast online learning that enhances system stability as compared to other neural networks (e.g. [49,51]). The Levenberg-Marquardt algorithm (LMA) is used as the learning algorithm to optimize the weight vector of ENRBFN. Besides, we define adaptive weight update that helps in the selection of appropriate LMA parameters and also ensures the asymptotic stability of the closed-loop system. An adaptive control law is designed based on Lyapunov stability theorem for practical trajectory tracking of attitude angles. Lyapunov based stability analysis is used to show that the adaptive control law provides desired trajectory tracking of attitude angles (pitch, roll and yaw) while keeping the closed-loop stable. Simulation results are provided to demonstrate the effectiveness of the proposed adaptive trajectory controller in the presence of wind disturbances. The Dryden turbulence model has been used in the simulation to produce wind disturbances close to actual operating conditions. Finally, the proposed ENRBFN based adaptive trajectory controller is applied to four rotor hover vehicle to validate the simulation results. The main contributions of the proposed work are:

1) The ENRBFN is introduced in this paper to approximate the unmodeled dynamics of the four rotor hover vehicle. The proposed ENRBFN can also be used for unmodeled dynamics estimation of other electromechanical systems.
2) The proposed controller has fast online learning as compared to the traditional neural network controllers.
3) The ENRBFN based adaptive trajectory controller effectively suppresses the wind disturbances.
4) The stability analysis is provided to show that tracking error is always within known limit.

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