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# Continuous ant colony filter applied to online estimation and compensation of ground effect in automatic landing of quadrotor

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ABSTRACT

The automatic landing of a quadrotor is often associated with model uncertainties, measurement noises, and ground effect phenomenon. To mitigate these challenges, the accurate estimation of states especially the height above the ground, and its rate of change is vital. Moreover, the error of ground effect model can also be estimated and compensated during landing. In this paper, the recently developed *continuous ant colony filter* is implemented for integrated estimation of states and parameters. The estimated states are used in height control loop. To investigate the closed loop performance of the filter, two control strategies, a classical proportional-integral-derivative controller and a sliding mode controller are utilized and their performance are compared in the presence of ground effect compensation and without it. Also, the error of ground effect model is estimated and compensated in landing algorithm. Finally, a landing procedure is proposed including a ground effect estimation phase before the touchdown. The simulation results show that the proposed algorithm effectively improves the landing performance when the ground effect is properly compensated. Moreover, small estimation errors, obtained from the simulations, prove the good performance of the new filter in states and parameters estimation.



## 1. Introduction

An Unmanned Aerial Vehicle (UAV) may have the capability of Vertical Take-off and Landing (VTOL). The most important features of VTOL UAVs are that they do not need runways for their operation and they can hover at a fixed point. Quadrotors are a kind of VTOL UAVs. High maneuverability, low pilot training time, easy manufacturing, low maintenance costs and low acoustic noises are the most advantages of quadrotors as compared to some other VTOLs. VTOLs have usually easier landing than other UAVs. However, landing phase is still the most difficult and dangerous part of the flight. Therefore, many works are being done on automatic landing of VTOLs as well as quadrotors.

The landing procedure of a VTOL UAV can be divided into two stages: descend and touchdown. Descend is the height gradual reduction from an initial flight condition to a specified height over the landing position. Touchdown, in comparison, refers to the process by which VTOL descends from the specified height till touching the ground. This stage is affected by the ground effect phenomenon.

Ground effect increases the rotor thrust at a given power (Johnson, 1994). Therefore, VTOLs can hover in ground effect at a higher gross weight than out of the ground effect. Hence, performing the touchdown phase by an operator is not only risky, but also requires a lot of skills. Similarly, performing an automatic landing with an autopilot needs accurate and high performance sensors and controllers. Such controllers usually require all state variables to generate control signals. In practice, some state variables are not measured. Therefore, it is necessary to estimate other states in order to utilize a full state feedback scheme. Moreover, some unknown parameters of the system may sometimes be estimated and compensated during the flight.

To perform a high performance touchdown, the accurate distance of quadrotor from the ground and its rate of change are required. Different filters have been used to estimate these parameters such as Kalman Filter (KF) (Grzonka et al., 2008, 2009, 2012; Waslander et al., 2005; Andreas, 2010; Watts, 2011; Bohdanov and Liu, 2012; Conroy et al., 2013), Extended Kalman Filter (EKF) (Kemp, 2006; Norafizah et al., 2012; Meyer et al., 2012; Serrano, 2011; Ireland and Anderson, 2012; Kis et al., 2008; Zhang et al., 2009; Kis and Lantos, 2012), and Unscented Kalman Filter (UKF) (Abas et al., 2011).

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KF (Kalman, 1960) is a linear filter. It assumes that the posterior Probability Density Function (PDF) is Gaussian and can be characterized by a mean and a covariance. KF has been used to estimate altitude and vertical velocity of a quadrotor in an indoor environment by combining inertial measurements, altitude measurements, and other sensors (Grzonka et al., 2008, 2009, 2012; Waslander et al., 2005; Andreas, 2010; Watts, 2011). In Bohdanov and Liu (2012), and Conroy et al. (2013), KF has been used to estimate altitude and vertical velocity of a quadrotor relative to a target.

EKF (Jazwinski, 1970) can be taken an analytical approximation nonlinear filter in to account since it linearizes nonlinear mathematical model of the system, and then the linear KF is used as well. In Kemp (2006) and Norafizah et al. (2012), EKF has been utilized to estimate the orientation, position and velocity of a quadrotor. In Meyer et al. (2012), the measurements of an Inertial Measurement Unit (IMU) are used to estimate some states of a quadrotor using EKF. Also, the data of IMU has been combined with additional sensors, including Global Position System (GPS) (Serrano, 2011; Ireland and Anderson, 2012) and vision system (Kis et al., 2008; Zhang et al., 2009; Kis and Lantos, 2012), to provide more observations for EKF.

Unlike EKF, UKF (Julier and Uhlmann, 1997) is a sample based filter. It does not approximate the nonlinear mathematical model. Instead, it approximates the posterior PDF by a set of deterministically chosen samples. In Abas et al. (2011), UKF has been used to estimate some states and parameters of a quadrotor, given the flight test data.

A class of sample based filters utilize heuristic algorithms to generate a set of samples within the state space and to improve the position of them. These filters are called heuristic filters (Nobahari and Sharifi, 2012). PF (Arulampalam et al., 2002) is an example of heuristic filters. It works based on point mass (or particle) representation of the probability densities (Arulampalam et al., 2002). Unlike UKF, PF represents the required posterior PDF by a set of random samples instead of deterministic ones. Also, it uses a resampling procedure to reduce the degeneracy of particle set. The standard resampling copies the important particles and discards insignificant ones based on their fitness.

A new class of heuristic filters, called swarm filters (Nobahari et al., 2013), utilizes swarm intelligence techniques to solve state estimation problems. Particle Swarm Optimized Particle Filter (PSOPF) (Tong et al., 2006), Ant Colony Optimization Assisted Particle Filter (PFACO) (Zhong et al., 2010), and Particle Filter with Ant Colony for Continuous Domains (Yu and Zheng, 2011) are examples of swarm filters. The authors have recently proposed Continuous Ant Colony Filter (CACF) (Nobahari and Sharifi, 2012; Nobahari et al., 2013) as a new swarm filter for nonlinear systems state estimation. This filter formulates the state estimation problem as a stochastic dynamic optimization problem and utilizes a colony of ants to find and track the best estimation. Ants search the state space dynamically in a similar scheme to the previously developed metaheuristic, known as Continuous Ant Colony System (CACS) (Pourtakdoust and Nobahari, 2004).

In this study, CACF is first utilized to estimate the height and vertical velocity of a quadrotor during the landing phase. To implement CACF, an accurate dynamic model is developed for a quadrotor in touchdown phase. Since this phase is affected by the ground effect phenomenon, the ground effect is modeled by inspiring from the similar available models in the literature. The proposed model simulates the change in thrust of each engine near the ground. Then, the estimated height and vertical velocity are used in the height control loop. Two known control strategies, a classical Proportional-Integral-Derivative (PID) controller and a sliding mode controller (SMC) are utilized for height control and their performance are compared in the presence of ground effect compensation and without it. Then, the error of ground effect parameters is also estimated and compensated in landing algorithm. Moreover, a landing procedure is proposed and its performance is investigated through simulation. The estimator proves to be well tuned and tested in open/close loop conditions. The simulation results show that the proposed algorithm effectively improves the landing performance when the ground effect is properly compensated. The small estimation errors, obtained from the simulations, prove the good performance of CACF in an engineering application.

This paper is organized as follows: Section 2 defines the automatic landing problem for a quadrotor. Section 3 is devoted to mathematical modeling of quadrotor and the ground effect. The estimation problem is formulated in Section 4. CACF is introduced in Section 5. Section 6 describes the landing program and the architecture of the altitude controller. Numerical results are provided in Section 7. Finally, a conclusion is made in Section 8.

## 2. Problem definition

Automatic landing is a challenging problem, since there is always model uncertainties, measurement noises and environmental disturbances. Moreover, the ground effect phenomenon occurs in this phase. Then, the accurate knowledge of states especially the height above the ground and its rate of change is vital. Therefore, the domain of focus in this paper is to estimate these states. Moreover, the ground effect parameters are going to be estimated. The landing phases of a quadrotor are illustrated in Fig. 1.

Fig. 2 shows the block diagram of the proposed landing algorithm. In dynamic modeling of quadrotor, it is assumed that the vehicle is rigid. Moreover, the dynamic model of altimeter is considered to be ideal while its output is corrupted by noise. Continuous Ant Colony Filter (CACF) uses the noisy output of altimeter to estimate the altitude and its rate of change. The altitude controller uses these information to follow the altitude command, issued by the landing program. In the following sections, the major steps of the automatic landing system are discussed in detail.

## 3. Mathematical modeling

In this section, first, a nonlinear dynamic model of the quadrotor is presented for control and estimation purposes. Then, the ground effect is modeled by inspiring from the similar available models in the literature. The proposed model simulates the change in thrust of each engine while the vehicle flies near the ground.

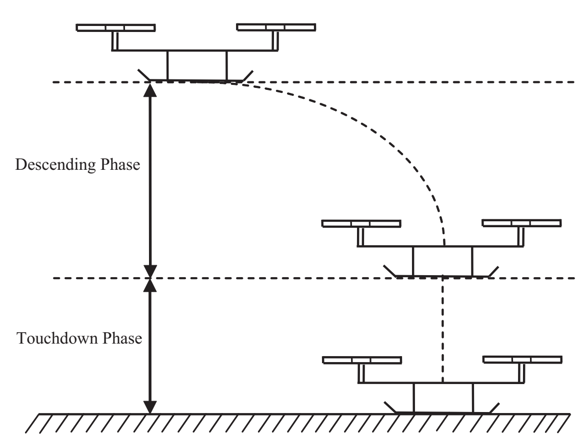


**Fig. 1.** Landing phases for a quadrotor.