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Automatic carrier landing control for unmanned aerial vehicles based on preview control and particle filtering ☆

Ziyang Zhen [a,b,*], Shuoying Jiang [a,b], Kun Ma [a,b]

[a] Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China
[b] No.29, Jiangjun Road, Nanjing, China

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ABSTRACT

For the carrier-based unmanned aerial vehicles (UAVs), one of the important problems is the design of an automatic carrier landing system (ACLS) that would enable autonomous landing of the UAVs on a moving aircraft carrier. However, the safe autolanding on a moving aircraft is a complex task, mainly because of the deck motion and airwake disturbances, and dimension limitation. In this paper, an innovative ACLS system for carrier-based UAVs is developed, which is composed of the flight deck motion prediction, reference glide slope generation and integrated guidance and control (IGC) modules. The particle filtering method is used to online predict the magnitudes and frequencies of the deck motion, which are used to correct the reference glide slope to achieve minimum dispersion around the ideal touchdown point. An optimal preview control (OPC) scheme is presented for the IGC subsystem design, which fuses the preview information of the reference glide slope, equality constraint of UAV dynamics and performance index function, and predicted information of the carrier deck motion. Simulation results of a nonlinear UAV model show the effectiveness of the ACLS system in carrier autolanding under the deck motion and airwake disturbances.

1. Introduction

With the successful carrier landing of the U.S. Navy's X-47B by an arresting cable in 2013, the era of carrier-based unmanned aerial vehicle (UAV) is coming. However, carrier autolanding presents one of the most critical problems faced by the carrier-based aircraft. The small space of the carrier deck along with the terrible marine environmental disturbances such as the deck motion and airwake impose severe limitations on the landing performance. To overcome these difficulties, a reliable automatic carrier landing system (ACLS) is indispensible to improve the automatic landing safety of UAV.

To maintain the predetermined flight speed, stabilize the flight attitude and track the reference glide slope, the flight control plays an important role in the autolanding of UAVs. Several control methods have been used in the design of the ACLS of the UAVs. Wadley et al. [1] designed an inner loop comprised of a desired dynamics regulator, a control allocation and optimization algorithm, and also designed a PID based outer-loop guidance law. The U.S. Navy Research Laboratory developed an attitude and path angle control system based on the PID control method for a close-in covert autonomous disposable aircraft [2]. Actually, the above traditional engineering control methods may achieve satisfied landing performance in normal situations [3]. However, it is difficult for them to track the randomly changed reference glide path under the deck motion disturbances. Therefore, some advanced control methods for the ACLSs have been investigated in recent years. The dynamic inversion control theory was applied to design an ACLS for the unmanned combat aerial vehicle, which relied on the exact system model [4,5]. After adding wind and sea state turbulence, the control performance was degraded. Zheng et al. [6,7] presented some improved back-stepping methods for carrier-based UAVs, which were able to provide accurate tracking under some unknown aerodynamic parameters and actuator faults. However, the complexity of controller design makes them difficult to implement in engineering. An adaptive controller based on the approximate dynamic inversion and neural network was developed as the attitude-command-attitude-hold portion of the vehicle's autopilot, which showed benefits over traditional controllers in robustness and tracking performance [8]. Moreover, some intelligent control methods have also sprung up, such as intelligent optimization control [9], neural network based adaptive control [10] and fuzzy integrated slide mode control [11]. They were fused with

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* Corresponding author at: Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China.
E-mail address: zhenziyang@nuaa.edu.cn (Z. Zhen).

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other methods to improve the control performance of the UAVs. However, they were difficult to be realized in real applications, and little literature considers the flight deck motion compensation and airwake rejection problems.

Preview control aims to solve the trajectory tracking and disturbance rejection problems where the signals to be tracked or rejected are available a priori by a certain amount of time. It has attracted many researchers for its applications in autonomous vehicles, robotics and process control. The applications of preview control for active vehicle suspension system [12,13], motor servo system [14], biped walking robot [15] and rotorcraft [16] have been presented. It is suitable for systems that have reference signals known a priori. For the carrier autolanding control problem, the glide path is previewable and the carrier deck motion is predictable. Therefore, this paper presents an optimal preview control (OPC) method for the carrier autolanding of the UAVs.

Different from the results in the literature, the main contributions of this paper are as follows:

1) The proposed OPC scheme utilizes the preview information of the reference glide slope, equality constraints of UAV dynamics and performance index function, to improve the landing path tracking precision of the carrier-based UAVs, which has not been reported in the literature. The OPC scheme is composed of a state feedback controller and a previewable reference signals feedforward controller. The nonlinear UAV model simulations verify the high landing precision of the OPC based ACLS system.

2) The deck motion prediction information is used to compensate the disturbance of the flight deck motion on the autolanding, which has not been studied in [1,2,6–9]. A particle filter is designed to predict the future information of deck motion, and the OPC based ACLS utilizes it to generate the feedforward compensation signal for disturbance rejection. The nonlinear UAV model's simulations verify the effectiveness in disturbance rejection of the ACLS.

3) The OPC based ACLS is characterized by integrated guidance and control (IGC), which is different from the carrier landing control methods in [1–4,6–8,10]. The IGC system is blended without separation of the inner-loop and outer-loop controllers design, which simplifies the design process of the ACLS.

The rest of this paper is organized as follows. In Section 2, the carrier autolanding problem is described. In Section 3, an ACLS framework for the carrier-based UAVs is developed. In Section 4, an OPC based IGC scheme is designed. In Section 5, the simulation results verify the desired system performance. In Section 6, we summarize our findings with conclusions.

2. Carrier autolanding problem of UAVs

In this section, the nonlinear UAV model, deck motion model and airwake model are formulated, and the carrier autolanding guidance and control problem of the carrier-based UAVs is described.

2.1. Modeling of UAV, deck motion and airwake

Nonlinear UAV model. The equation of motion (EOM) set of the fixed-wing UAV is a fully-coupled nonlinear differential equations in a non-rotating Earth inertial reference frame, given by [17,18]

$$\begin{cases} \dot u = vr - wq - g\sin\theta + \frac{F_x}{m} \\ \dot v = -ur - wp + g\cos\theta\sin\phi + \frac{F_y}{m} \\ \dot w = uq - vp + g\cos\theta\cos\phi + \frac{F_z}{m} \end{cases} \tag{1}$$

$$\begin{cases} \dot p = (c_1 r + c_2 p)q + c_3 \bar L + c_4 N \\ \dot q = c_5 pr - c_6(p^2 - r^2) + c_7 M \\ \dot r = (c_8 p + c_2 r)q + c_4 \bar L + c_9 N \end{cases} \tag{2}$$

$$\begin{cases} \dot X = V\cos\mu\cos\varphi \\ \dot Y = V\cos\mu\sin\varphi \\ \dot H = V\sin\mu \end{cases} \tag{3}$$

$$\begin{cases} \dot\phi = p + (r\cos\phi + q\sin\phi)\tan\theta \\ \dot\psi = \frac{1}{\cos\theta}(r\cos\phi + q\sin\phi) \\ \dot\theta = q\cos\phi - r\sin\phi \end{cases} \tag{4}$$

$$\begin{cases} \dot V = \frac{u\dot u + v\dot v + w\dot w}{V} \\ \dot\alpha = \frac{u\dot w - w\dot u}{u^2 + w^2} \\ \dot\beta = \frac{v\dot V - V\dot v}{V^2\cos\beta} \end{cases} \tag{5}$$

Thus, the nonlinear UAV model can be expressed by

$$\dot x = f(x, u) \tag{6}$$

where $x = [V, \alpha, \beta, \theta, \phi, \psi, p, q, r, H, Y]^T$, denoting the airspeed, angle of attack, sideslip angle, roll, pitch and yaw angles and angular rates, height and lateral deviation, respectively. $u = [\delta_e, \delta_T, \delta_a, \delta_r]^T$, denoting the elevator, throttle, aileron and rudder deflections, respectively.

Deck motion model. The sea wave motion is generally considered as a stable random process with a narrow bandwidth. Durand presented a power spectrum based deck motion model [19]. The power spectral density function curves can be obtained by the experiments or simulations, which are used to find the optimal coefficients, and then a shaping filter can be constructed. The time domain information of the deck motion is obtained by filtering the white noise through the shaping filter. A general model for the translational deck motions (surge, sway, heave) is given by [19]

$$G(s) = \frac{a_1 s^2 + a_2 s + a_3}{s^4 + b_1 s^3 + b_2 s^2 + b_3 s + b_4} \tag{7}$$

and a general model for the angular deck motions (pitch, roll, yaw) is given by

$$G(s) = \frac{a_1 s + a_2}{s^4 + b_1 s^3 + b_2 s^2 + b_3 s + b_4} \tag{8}$$

where $a_1 \sim a_3, b_1 \sim b_4$ are the constant coefficients.

Airwake model. A general carrier airwake disturbance model is composed of free air turbulence component (u_1, v_1, w_1), steady component (u_2, w_2), periodic component (u_3, w_3), and random component (u_4, v_4, w_4), given by [20]

$$\begin{cases} u_g = u_1 + u_2 + u_3 + u_4 \\ v_g = v_1 + v_4 \\ w_g = w_1 + w_2 + w_3 + w_4 \end{cases} \tag{9}$$

where u_g denotes the axial airwake, v_g denotes the side airwake, w_g denotes the normal airwake. The specific mathematical equations of the four components of airwake can be found in [20].

2.2. Autolanding problem of UAV

Difficulties of the carrier autolanding. There are several reasons why the carrier autolanding of the UAVs is a very difficult task. First, the landing must be performed in the presence of carrier deck motion, air wake and normal air turbulence. Especially, the carrier deck motion is the main factor which can greatly complicate this process. Second, the UAVs usually have unstable dynamics at low approach speeds, because they are usually operating on the backside (unstable) region in the landing phase. Therefore, to achieve a carrier autolanding, an automatic power compensation is necessary for the landing speed keeping control through adjusting the throttle opening. Third, the UAVs must be high enough to clear the carrier ramp, but low enough to catch the number 4 wire

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