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Relative position control design of receiver UAV in flying-boom aerial refueling phase

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ABSTRACT

This paper proposes the design of the relative position-keeping control of the receiver unmanned aerial vehicle (UAV) with the time-varying mass in the refueling phase utilizing an inner-outer loop structure. Firstly, the model of the receiver in the refueling phase is established. And then tank model is set up to analyze the influence of fuel transfer on the receiver. Subsequently, double power reaching law based sliding mode controller is designed to control receiver translational motion relative to tanker aircraft in the outer loop while active disturbance rejection control technique is applied to the inner loop to stabilize the receiver. In addition, the closed-loop stabilities of the subsystems are established, respectively. Finally, an aerial refueling model under various refueling strategies is utilized. Simulations and comparative analysis demonstrate the effectiveness and robustness of the proposed controllers.
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1. Introduction

The history of air-to-air refueling (AAR) can be tracked back to the 1910s [1]. AAR has since been developed into the established methods [2] to enlarge the payload, endurance, and range of manned aircraft. The growing application of unmanned aerial vehicles (UAVs) results in a desire to improve their versatility which contains ability of performing AAR. It is the requirement that facilitates the research and development of automated air-to-air refueling (AAAR).

To date, there are two prevalent refueling methods, such as flying-boom refueling and probe-drogue refueling. In the former refueling, a telescopic boom, including an anchored boom and a boom extension, is extended from the tanker aircraft. It is steered by the two aerodynamic control surfaces located at the free end of the telescopic boom to a successful docking. In the term of the probe-drogue refueling, the drogue is trailed from a refueling hose and the probe is mounted externally on the receiver aircraft. Flying-boom refueling utilizes rigid boom to transfer fuel which is not susceptible to aerodynamic disturbances, providing significantly higher fuel transfer speed than probe-drogue refueling which causes faster change in the receiver's mass, center of mass and inertia matrix. The main drawback of flying-boom method is the fact that only one receiver aircraft can be serviced at any time due to the complexity and weight of the boom. Although the drogue is subject to aerodynamic effect from tanker, receiver and turbulence, which makes it difficult for the receiver to capture the drogue, it is possible to service several aircrafts under probe-drogue method simultaneously. Probe-drogue refueling is suitable for refueling helicopters. The key point arises in the refueling phase of flying-boom refueling or docking phase of probe-drogue refueling from the view of receiver control, namely, relative position-holding control or drogue-tracking control. The former is taken into account in this paper. The difficulties in relative position control problem are summarized as (1) the dynamics of receiver is highly nonlinear, fast time-varying and strongly coupling in flying-boom aerial refueling phase; (2) receiver is the presence of external aerodynamic disturbances containing atmospheric turbulence and tanker's wake vortex. Therefore, the flight control of receiver cannot be neglected, and the control strategies require strong robustness against model uncertainties and external aerodynamic disturbances when receiver operates flying-boom aerial refueling.

In order to address the relative position control problem, several control approaches for receiver have been proposed. In [3,4], a position-tracking controller was designed for receiver via a combination of LQR-based MIMO state-feedback and integral control to keep receiver's position relative to tanker in the presence of trailing vortex and turbulence. However, the effect of fuel transfer on receiver's dynamics was not considered. In the linearized equation of receiver, the impact of the tanker motion on the relative motion was clearly identified by a matrix, which was not

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used in the control design. In [5], the dynamics equations of receiver aircraft in refueling phase were derived considering the varying fuel mass of receiver. The receiver model incorporated the wind effect terms and their time derivatives. And the control techniques from [3] were used to develop a position controller for receiver. In [6], combining a disturbance rejection method with the approaches from [3], a new scheme was employed for improving receiver's tracking performance on the refueling position. Nevertheless, the total mass of receiver was constant in the simulations to evaluate the closed loop performance. All the controllers above are linear which provide good flight performance for small regions about the trim conditions. In general, gain scheduling is employed to enlarge the available range of the linear controller. In [7], exact Nonlinear Dynamic Inversion (NDI) was performed to design the relative position controller of the receiver aircraft based on the kinematic models. NDI was only applied to the relative position control outer loop. As is known to all, the performance of the controller depends on the model accuracy. The exact mathematical model is considerably sophisticated, which makes control law complicated. However, complicated control law is not attractive from the implementation point of view.

To solve the aforementioned problems, one of the solutions is the Active Disturbance Rejection Control (ADRC), which is well effective for nonlinear system with both external disturbances and internal uncertainties and extensively used in the design of the flight control system. For example, it has been applied to the longitudinal control of micro-aerial vehicle (MAV) [8], coaxial-rotor UAV trajectory tracking [9], attitude control of fixed wing UAV [10,11], hypersonic reentry vehicle (HRV) attitude tracking [12], and helicopter trajectory tracking [13]. The dependence on the plant's mathematical model is relaxed in ADRC technique whose main idea is online estimation and compensation of the influence of the total perturbation, lumping unmodeled dynamics, uncertainties, and external disturbances, via the extended state observer (ESO), a key component of ADRC [14,15]. Besides the relative order of the plant to be controlled, very little knowledge of the plant is required to design a robust controller based on the ADRC technique. On the other hand, sliding mode control (SMC), which is also an effective nonlinear control approach, has been widely investigated due to its simple process for design and robustness against uncertainties [16–18]. The main disadvantage of the conventional SMC based controller ensuring robustness against uncertainties is high frequency switching of the control signal, namely, chattering. To overcome this drawback, a global fast dynamic terminal sliding mode control method was proposed in [17], and the extended disturbance observer was utilized in [18]. These controllers based on both ADRC and SMC perform well in robustness, respectively. Another task is to design the control system structure to implement relative position-holding performance for receiver in flying-boom refueling process. Different from the attitude control of aircraft, the design of position controller is relatively complicated [19] on account of the fact that the higher relative degree of the position coordinates. To simplify the design of the control system we use idea from hierarchical approach yielding inner and outer control loops. The inner loop is designed to control the attitude and airspeed while the outer loop is designed to control the translational motion of receiver.

The receiver model from [5] describes the position and orientation of receiver relative to tanker instead of ground. Although it is clear to present the relative motion of receiver with respect to tanker in this way, these states cannot be directly measured [20] which are used in control laws. What's more, introducing wind effect terms makes the receiver's mathematical model considerably complex. Hence, we derive the dynamics equations of the receiver relative to ground considering variable mass and inertia matrix, adopting a simple but effective method from [21] to introduce the external aerodynamic disturbances into the receiver model. To research the effect of fuel transfer on the receiver's dynamics, a simple tank model is established. It is crucial to hold the position of receiver relative to tanker aircraft. For the sake of the receiver's position-keeping performance, a SMC based controller is implemented as an outer loop controller. To address the chattering, we design double power reaching law for outer loop controller which has the characteristic of global fixed-time convergence [22–24]. For another thing, we develop inner loop controllers employing ADRC technique. Eventually, a detailed aerial refueling model is comprised of a tanker aircraft model representing KC-135R, a receiver aircraft model, wake vortex model, and atmospheric turbulence model. The receiver model is a tailless delta wing fixed-wing unmanned aerial vehicle with the innovation control effector (ICE). The main contributions of this paper can be summarized as follows:

(i) A receiver model with time-varying fuel mass is proposed in this paper. This receiver model is independent on the fuel tank configuration, which facilitates the research of asymmetric refueling conditions.
(ii) This paper utilizes an inner-outer loop structure to combine ADRC method and double power reaching law-based SMC technique for receiver. Compared with [5–7], this method of designing controller is simplified and the controllers have stronger robustness against external aerodynamic disturbance and model parameters' variations.
(iii) Fruitful attempt is made to treat unmodeled dynamics and variations of model parameters as internal uncertainties. This paper treats internal uncertainties and external aerodynamic disturbances as total disturbance. This novel idea along with ESO reduces dependence on the accurate receiver model in the process of designing controller.

The rest of this paper is organized as follows. Section 2 introduces model of receiver aircraft under the consideration of the time-varying fuel mass during the refueling operation. Section 3 presents the analysis of the impact of refueling on receiver in detail in term of the center of mass. Section 4 incorporates the control design for the receiver aircraft and the stability analysis of closed-loop system. Section 5 discusses simulation environment and a set of simulation results under various condition of refueling strategies. Finally, the conclusion of this paper is given in Section 6.

2. Model of receiver aircraft with mass variation

In this section, a brief study about the model of receiver aircraft which is a fixed-wing UAV during the refueling operation is introduced [5].

In order to facilitate the derivation of the receiver dynamics model the following reference frames are used: inertia frame I, receiver's body frame B_R, receiver's wind frame W_R, tanker's body frame B_T, and tanker's wind frame W_T. Before the start of refueling I, B_R, and B_T are defined in Fig. 1 where the vectorial relation of the origins of three reference frames yields

$$\underline{\xi} = \underline{r}_{B_R} - \underline{r}_{B_T} \tag{1}$$

Translational motion of the receiver is described by (2) and (3). Moreover, rational motion is represented via (4) and (5).

$$\dot{\mathbf{r}}_{B_R} = \mathbf{R}_{B_R I}^{T}\mathbf{R}_{B_R W_R}\mathbf{V} \tag{2}$$

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