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Exact docking flight controller for autonomous aerial refueling with back-stepping based high order sliding mode

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ABSTRACT

Autonomous aerial refueling (AAR) exact docking control has always been an intractable problem due to the strong nonlinearity, the tight coupling of the 6 DOF aircraft model and the complex disturbances of the multiple environment flows. In this paper, the strongly coupled nonlinear 6 DOF model of the receiver aircraft which considers the multiple flow disturbances is established in the affine nonlinear form to facilitate the nonlinear controller design. The items reflecting the influence of the unknown flow disturbances in the receiver dynamics are taken as the components of the ‘‘lumped disturbances” together with the items which have no linear correlation with the virtual control variables. These unmeasurable lumped disturbances are estimated and compensated by a specially designed high order sliding mode observer (HOSMO) with excellent estimation property. With the compensation of the estimated lumped disturbances, a back-stepping high order sliding mode based exact docking flight controller is proposed for AAR in the presence of multiple flow disturbances. Extensive simulation results demonstrate the feasibility and superiority of the proposed docking controller.

1. Introduction

With the persistently increasing number of unmanned aerial vehicles (UAVs) in modern military mission [1,2], the autonomous aerial refueling (AAR) [3], which enables aircraft to extend endurance and save loiter time on station by transferring fuel from the tanker aircraft to the receiver aircraft, has been an active topic [3,4]. It has drawn more and more significant interests from the research and development community [5–8], especially for the purpose of enabling unmanned aerial vehicles with this critical capability. Generally, there are two major types of aerial refueling in operation [3]: probe-drogue refueling (PDR) and boom receptacle refueling (BRR), and both play important roles in modern civil and military applications. In either case, it would be better if the receiver aircraft were exactly controlled for aerial refueling. In this paper, we focus on the probe-drogue refueling (PDR) [9,10], as shown in Fig. 1. The tanker aircraft trails a flexible refueling hose and the drogue at the end of the hose. The hose-drogue aerial refueling system in the PDR, which dragged by the flying tanker, is simple to be adapted to many existing aircrafts and can simultaneously refuel multiple receiver flights.

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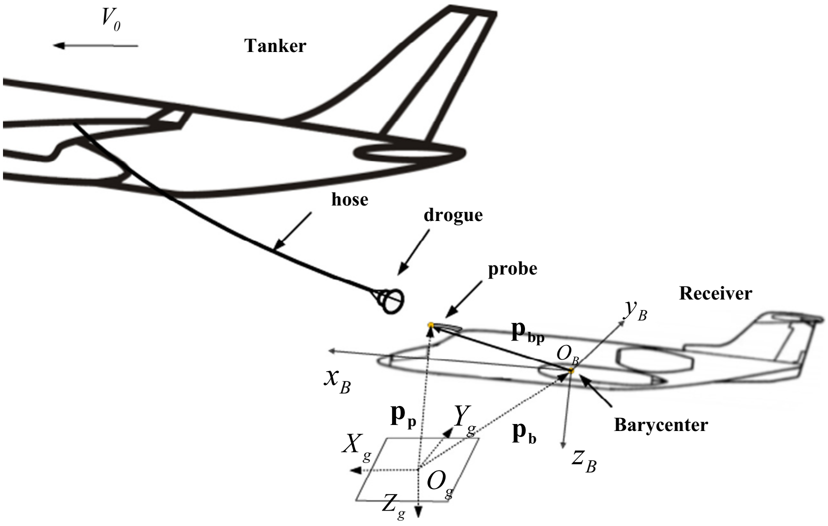

Fig. 1. The configuration of a PDR system.

In a PDR, the receiver's probe is conducted to capture the wobbly drogue which is affected by the tanker's motion and the multiple flow disturbances including tanker trailing vortex, bow wave and atmospheric turbulence [3,9,11]. Besides, the motion of the controlled receiver is much slower than fleetly swinging drogue [3,9]. That makes it more intractable for the receiver to track the transient changing drogue. These particularity facts during the AAR docking pose great challenges on the design of a robust and exact docking controller.

Although there have already been some previous works [12–21] discussing docking flight controller design for the receiver aircraft, unfortunately, few kinds of literature focus on the above problems during the controller design process. The existing literature mostly designs receiver trajectory tracking controller with the Linear Quadratic Regulator (LQR) theory [3,12–18]. However, LQR theory uses the linearized nominal plant model to design the controller [13], and the anti-disturbance ability for the unknown flow disturbances are not considered during the controller designing. Actually, the receiver's motion is affected by the stochastic atmospheric turbulence and the tail vortex field generated by the front tanker aircraft [3,5,9]. Moreover, the docking accuracy requirement is very high, and these flow disturbances will definitely affect the receiver' motion, or even lead to the docking failure. On one hand, the amplitude and direction of the surrounding atmospheric turbulence are unpredictable. On the other hand, the amplitude and direction of the tail vortex which acts on the receiver's body and wings will be very different due to the large scale of the receiver in the vortex. The position and attitude changing of the receiver will definitely cause considerable changing of the amplitude and direction of the tail vortex that acts on the receiver. These external flow disturbances may pose a serious impact on the LQR controller as it does not possess special anti-disturbance mechanism. This poorer anti-disturbance ability may even cause the failure of the AAR docking if the flow disturbances are strong enough. Another linear model based method known as L1 adaptive control methodology is adopted in AAR [19], but the same problem of lacking satisfied anti-disturbance ability will also be faced. And it will also not ensure the receiver's high tracking performance to the fast moving drogue. The nonlinear dynamic inversion (NDI) is also tried to be applied to the receiver tracking control in AAR together with some uncertainty compensation technique [20–22]. However, these existing NDI based flight controllers are generally designed only in the attitude control loop. As the flow disturbances directly affect the aerodynamic forces on the receiver, and the aerodynamic forces will directly affect the receiver's translational dynamics, these controllers cannot well ensure the satisfactory anti-disturbance ability in the receiver's flight path or position loop. Moreover, the neural network based techniques are generally used as common techniques for the disturbance compensation in the NDI based controller [20–22]. But the complexity of the neural network parameters tuning will also limit its application in AAR.

Actually, few papers designed the AAR position tracking controller entirely based on the 6 DOF nonlinear receiver model via a unified nonlinear control method (for instance, the NDI). This is because the 6-DOF nonlinear model of the receiver will be non-affine, coupled and particularly complex when the influence of the multiple flow disturbances is considered [9], especially in translational dynamics of the receiver. This also poses an extra challenge on the receiver docking controller. Although the author's previous work in [9] tried to design the active disturbance rejection control (ADRC) [23–25] based docking controller via the disturbances or uncertainties compensation technique by the extended state observer (ESO) [26,27], the tracking performance for the fast moving drogue is still urgently needed to be improved. As the controlled receiver's motion is much slower than the fast changing drogue, the relatively simple control structure of the linear ADRC can still not achieve satisfied tracking performance for the drogue, and the docking success rate is still needed to be improved. Thus,