Aerospace Science and Technology 56 (2016) 34–45

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

A robust back-stepping based trajectory tracking controller for the tanker with strict posture constraints under unknown flow perturbations

Zikang Su [a,b,c], Honglun Wang [a,c,*], Xingling Shao [a,c], Yu Huang [a,c]

[a] *School of Automation Science and Electrical Engineering, Beihang University, 100191, Beijing, China*
[b] *Honors College of Beihang University, 100191, Beijing, China*
[c] *The Science and Technology on Aircraft Control Laboratory, Beihang University, 100191, Beijing, China*

ARTICLE INFO

Article history:
Received 25 March 2016
Received in revised form 16 May 2016
Accepted 1 July 2016
Available online 12 July 2016

Keywords:
Autonomous aerial refueling
Tanker flight control
Barrier Lyapunov function
Active disturbance rejection control
Back-stepping

ABSTRACT

This paper proposes a novel robust back-stepping based trajectory tracking controller for the tanker with strict posture constraints under unknown flow perturbations in Autonomous Aerial Refueling (AAR). Firstly, by using the back-stepping technique, the proposed trajectory tracking control law design is separated into five loops. The 6 DOF model for tanker is tactfully transformed into several strict-feedback nonlinear forms, especially the dynamics of the translational kinematics which are originally non-affine nonlinear forms and are intractable for controller design. The influences of the unknown flow perturbations on tanker in each loop are viewed as the components of the “total disturbances” which are estimated and compensated by extended state observer (ESO). Secondly, the uncontrolled Euler angle constraints, which should also be considered in AAR, are transformed into extra boundary commands for the angular rates. And a novel command limiting tracking differentiator (CLTD), which considers not only the controlled but also uncontrolled state constraints, is specially designed for posture control. Thirdly, an integrated robust constrained posture control scheme is proposed for tanker's posture constraints based on Barrier Lyapunov (BL) function and CLTD. Then, with the position and ground velocity controller based on traditional active disturbance rejection control (ADRC) in the outer loop, a novel robust back-stepping based trajectory tracking controller is proposed for tanker in AAR. Finally, extensive simulations and comparisons on the 6 DOF tanker model are carried out to demonstrate the effectiveness of the proposed control scheme.

1. Introduction

Over the last decade, there has been a wealth of research and academic publications on theoretical and practical aspects of the Autonomous Aerial Refueling (AAR) [1] which is an effective method of increasing the endurance and region of the aircrafts. In this paper, we focus on the probe–drogue refueling, as shown in Fig. 1. In the aerial refueling flight control system design, most of the attention is paid to the receiver's flight controller design to directly obtain a satisfactory autonomous refueling [2–8]. Actually, the performance of an aerial refueling operation depends on the motion of tanker as much as the motion of the receiver [9], especially in the probe–drogue refueling.

Although there have already been some previous works [2–8] discussing flight controller design for the receiver aircraft, it will be ill-considered if receiver's flight controller design is directly applied to the tanker, because the missions for these two aircrafts are certainly different. The flight controller of receiver is designed to ensure the probe on the receiver tracks the drogue rapidly and accurately under the influence of tanker's trailing vortex and atmospheric perturbation [1]. And as the location of the drogue is relatively far from the tanker's body, the limitations of the change of the receiver's barycenter and posture are not generally considered during controller designing. However, these limitations certainly cannot be ignored when designing the tanker's flight controller, because the tanker's flight controller is designed to ensure the desired fixed straight level flight [1,5,9] can be achieved on the condition that the tanker's posture changes as small as possible. Actually, the slight changes in the tanker's barycenter and posture will definitely cause considerable position changes of the drogue

---

[*] Corresponding author at: School of Automation Science and Electrical Engineering, Beihang University, 100191, Beijing, China.
E-mail address: hl_wang_2002@126.com (H. Wang).

http://dx.doi.org/10.1016/j.ast.2016.07.001

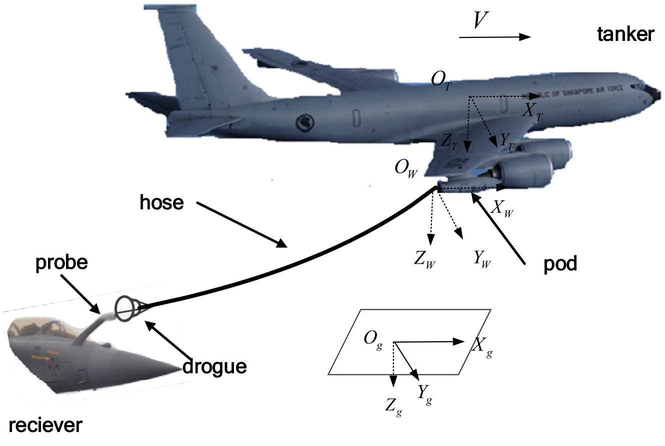

Fig. 1. The configuration of a hose–drogue aerial refueling system.

finally. Namely, a specially designed controller is needed for the tanker's specific flight mission.

Actually, the tanker is required to fly at a fixed height with a fixed ground speed and no lateral offset. Although a relative fair-weather is usually selected to conduct the aerial refueling, the unavoidable external disturbances, for instance the unknown flow perturbations, are always existing during the process. These disturbances will always cause unexpected motion on tanker. And it's obvious that the influence of the tanker's unexpected motion will be especially remarkable in the probe–drogue refueling system. On one hand, the refueling pod is generally located at the wingtip of the tanker, and the slight changes in tanker's barycenter position and the posture will cause considerable movement of the pod; on the other hand, the movement of the pod will cause more severe swing of the drogue through the long hose (generally, tens of meters).

Unfortunately, few literatures focus on tanker's accurate trajectory tracking control under unknown flow perturbations. And the existing literatures mostly design tanker trajectory tracking controller with the Linear Quadratic Regulator (LQR) theory [1,9–11]. However, the LQR theory uses the linearized nominal plant model to design the controller, and the unknown flow perturbations are not considered during the controller designing. Its disturbance rejection mechanism is passive, and the disturbance rejection ability only depends on the nominal designed controller. What's more, the LQR existing framework cannot take the state constraints into consideration. It makes that the desired posture constraints cannot be guaranteed via LQR. All of the above issues pose challenges on the specific mission of tanker flight controller from theoretical and practical perspectives.

Contrary to the existing LQR method for tanker flight controller design, a new active disturbance rejection tanker flight controller, which strictly ensures the desired flight can be achieved even under unknown flow perturbations, needs to be designed for AAR. Compared to the conventional LQR controller design process, there are some new problems that must be correspondingly considered: i) the disturbance rejection should be considered during the controller designing; ii) the tanker's barycenter position must be controlled at the desired condition; iii) the posture variables of tanker must be always constrained in the required domains.

Recently, active disturbance rejection control (ADRC) has been well developed for nonlinear uncertain system control problems [12–21]. All factors that affect the plant, such as system nonlinearities, uncertainties, and external disturbances are treated as a "total disturbance" in ADRC. And the "total disturbance" is observed and compensated by extended state observer (ESO) which is relatively independently of mathematical model of the plant, offers better performance, and is simpler to implement [14]. Then, combined with a simple feedback linearization method (see linear ADRC [13,14]), the nominal performance for closed-loop system can be recovered if the "total uncertainty" is timely compensated via ESO [15]. However, the existing standard ADRC is only available for integral chain systems that satisfy the so-called matching conditions [12–14], such as the motion control system [12] and actuated MEMS device [20]. Since the translation kinematics equations of a considered fixed wing aircraft are usually formulated as a non-affine nonlinear system in flight-path axis [21], a problem arises naturally, how to extend the existing ADRC technique to the translation kinematics controller design by back-stepping. To our best knowledge, few efforts have been contributed to this issue.

Inspired by the function of ESO above, the translation kinematics equations are transformed to a strict-feedback nonlinear subsystem in this paper, and the introduced items in the transformed equations are all taken as a part of the "total disturbance" which are then observed and compensated by ESO. Then, by the back-stepping technique, the tanker trajectory tracking control system can be designed through five independent control loops: position loop, flight path loop, attitude loop (flow angles or Euler angles control), angular rate loop and ground velocity loop. And it seems that the former two problems of tanker trajectory tracking control mentioned above can be resolved by this way. Unfortunately, the existing ADRC performs powerlessly for state constraints problem in the posture control. Although [15] proposed an integrated guidance and control system based on ADRC, the state constraints are still not considered. Therefore, a specially designed posture control scheme must be introduced for the posture constraints problem that involves not only flow angles but also Euler angles.

The control scheme based on Barrier Lyapunov (BL) function, which is firstly proposed by Ngo [22,23], provides a solution for nonlinear system with state constraints. It exploits the property that a BL function grows to infinity whenever its arguments approach some limits. By keeping the BL function bounded in the closed loop system, it thus guarantees that the barriers are not transgressed. Tee [24–26] extended BL to asymmetry BL for the strict-feedback nonlinear system with parameter uncertainties, and researched the control law design and stability analysis when output constraints [24], full state constraints [25], partial state constraints [26] exist, respectively. In this paper, we try to introduce the BL function based control scheme to the posture control for the tanker's posture constraints problem. But there is still an important accessory problem needing to be taken into consideration. Generally, the attitude loop control is achieved by the control of either flow angles or Euler angles. That means if we adopt the flow angles control scheme, the flow angles will be controlled states [25–27], and the Euler angles will become uncontrolled states. And the desired Euler angle constraints cannot be guaranteed by the existing control scheme based on BL function. Therefore, a novel command limiting tracking differentiator (CLTD), which considers the Euler angle constraints in the posture controller design, is presented based on the traditional tracking differentiator (TD). The Euler angle constraints are transformed into the extra boundary commands for the angular rates via CLTD. By these techniques, an integrated control scheme of the attitude loop and angular rate loop is achieved to limit the controlled and uncontrolled states into the desired domains.

Inspired by the above analysis, we investigate in this paper the feasibility of a novel back-stepping based trajectory tracking controller for tanker with strict posture constraints under unknown flow perturbations. The main contributions in this paper can be summarized as follows:

(i) A novel robust back-stepping based trajectory tracking control scheme, which combines ADRC and BL function method,