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Fractional-order controllers optimized via heterogeneous comprehensive learning pigeon-inspired optimization for autonomous aerial refueling hose–drogue system

Yongbin Sun, Haibin Duan*, Ning Xian

State Key Laboratory of Virtual Reality Technology and Systems, Beihang University, Beijing 100083, China

ARTICLE INFO

Article history:
Received 4 February 2018
Received in revised form 20 July 2018
Accepted 23 July 2018
Available online xxxx

Keywords:
Autonomous aerial refueling (AAR)
Hose–drogue system (HDS)
Controllable drogue
Optimized fractional-order controller (FOC)
Heterogeneous comprehensive learning pigeon-inspired optimization (HCLPIO)

ABSTRACT

Dynamic modeling and control system design for the hose–drogue system (HDS) in the docking stage of autonomous aerial refueling (AAR) are investigated in this paper. The dynamics and kinematics of hose are modeled via a finite-segment multi-body method, which describes the hose–drogue assembly as a link-connected system. A controllable drogue is connected to the hose for automatically stabilizing the drogue's relative position under the influences of tanker trailing vortex, receiver bow wave, atmospheric turbulence, gust, and wind shear. Thus, a drogue position control law based on fractional-order method is designed to resist the multi-wind disturbances. Noting that it is difficult to tune the parameters of fractional-order controller (FOC), a modified pigeon-inspired optimization (PIO), the hybrid of heterogeneous comprehensive learning strategy and PIO (HCLPIO), is carried out to optimize the parameters of FOC. The simulation results show that the proposed optimized fractional-order feedback controllers effectively stabilize the controllable drogue to swing within an acceptable range.

1. Introduction

Aerial refueling has been regarded as an effective method of increasing the endurance and range limitations of aircrafts. For manned aircrafts, if the pilots are not skilled for aerial refueling, autonomous aerial refueling (AAR) [1] would commendably assist the pilots to accomplish the task. And for unmanned aerial vehicles (UAVs), if UAVs have the ability of AAR, the autonomy of UAVs [2] would be enhanced drastically, which is a developing tendency of UAVs. Thus, AAR has drawn substantial interest from research institutions inspired by an advanced integration of UAVs into current combat missions [3,4]. Basically, three approaches are practiced for aerial refueling: the boom-receptacle refueling (BRR) [5,6], which the tanker extends the retractable boom to the fuel receptacle of receiver; the probe-and-drogue refueling (PDR) [5,6], which the tanker drags a flexible hose with a drogue and the receiver aims at inserting the probe into the drogue; the boom drogue adapter units refueling [6,7], which is the combination of the above two refueling approaches by attaching the drogue adapter units to the boom. Compared to the other two approaches, PDR outstands in certain aspects: in the processes of PDR, the receiver need not hold a strict relative position to the tanker and multiple receivers can be simultaneously refueled by a tanker equipped refueling pods. Besides, PDR is the only approach for helicopter refueling.

However, the hose–drogue assembly suffers complicated multi-wind disturbances in the processes of PDR. There always has atmospheric turbulence, gust, and wind shear in the refueling scene. Besides, the tanker and receiver respectively generate the trailing vortex and bow wave, which have different intensity concerned with the relative position of tanker and receiver. The composite multi-wind disturbances induce the hose–drogue assembly swinging dramatically, which is adverse for the accurate docking. Hence an active-control method is essential for stabilizing the drogue to swing within an acceptable range for easy and secure refueling.

To further investigate the AAR accurate docking technique, many research institutions and scholars have implemented substantial experiments and modeling analysis for the hose–drogue system (HDS). NASA Dryden Flight Research Center [8,9] gathered abundant aerodynamic data by flight tests and wind tunnel, which is obliged for modeling the dynamics of HDS. Besides, the Boeing Company [10] presented a wing-pod refueling hose model to describe the dynamic characteristics of the hose. Zhu and Meguid [11] investigated the dynamic behavior and stability of the HDS model via the finite element method with an accurate and computationally efficient curved beam element. Moreover, Ro et al. [12] modeled the dynamics of the hose–paradrogue assembly via a finite-segment approach and studied the dynamic charac-

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* Corresponding author.
E-mail address: hbduan@buaa.edu.cn (H. Duan).

https://doi.org/10.1016/j.ast.2018.07.034
1270-9638/

Please cite this article in press as: Y. Sun et al., Fractional-order controllers optimized via heterogeneous comprehensive learning pigeon-inspired optimization for autonomous aerial refueling hose–drogue system, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.07.034

teristics of paradrogue assembly resulting from the atmospheric turbulence and tanker maneuver. Williamson et al. [13] developed a pendulum-based hose model combined with the model of aerodynamic drogue, which could be automatically controlled and stabilized using drogue canopy manipulation under the influences of multi-wind disturbances. Wang et al. [14] investigated the dynamic modeling of the variable-length hose–drogue system and designed a sliding mode backstepping controller for hose whipping phenomenon. As mentioned above, although the analysis and models present the dynamics of HDS, the effective active-control method for hose–drogue assembly should be exploited to stabilize the drogue's relative position in the presence of composite multi-wind disturbances.

The existing literatures mostly design the HDS controller with proportion–integration–differentiation (PID) [15]. Though the form and physical meaning of PID are explicit, the control effect would be influenced by many existing factors. The insufficient stability of PID controller for controllable drogue's position could be caused by the atmospheric turbulence and wind shear during the docking coupling. Another method known as linear quadratic regulator (LQR) [16,17] theory is also adopted for controller design. However, the dynamic model of hose–drogue assembly is nonlinear, and many feedback control states could not be measured. Thus, in this paper, fractional-order control theory [18,19] is proposed to design the fractional-order PID (FOPID) controllers for controllable drogue, which stabilizes the three-dimensional position of drogue with accessible control states regardless of linear or nonlinear HDS model. Nevertheless, the integral and derivative orders λ, μ are introduced into FOPID controller so that the difficulty of parameter tuning is rapidly enhanced due to the five-dimensional parameter $k_P, k_I, k_D, \lambda, \mu$. The inappropriate parameters could generate non-optimal system performance, so much so that induce the dramatical swing or divergence of drogue's position. Hence we adopt the modified evolutionary algorithm to optimize the capability of FOPID controllers for HDS and reduce the workload of designers.

Evolutionary algorithms (EAs), including genetic algorithm (GA) [20], particle swarm optimization (PSO) [21], artificial bee colony optimization (ABC) [22], and so on, have gathered considerable attention from optimization communities and have been successfully applied to a wide range of scientific research problems [23–25]. Pigeon-inspired optimization (PIO), a novel swarm intelligence optimization algorithm, was firstly proposed for path planning by Duan et al. [26]. For further applications of PIO, Li and Duan [27] accomplished the target detection task for UAVs, and Zhang et al. [28] solved the optimal formation reconfiguration problems of multiple orbital spacecrafts. Besides, Sushnigdha et al. [29] utilized the PIO to design a constrained entry trajectory of re-entry vehicles. Moreover, Zhao et al. [30] applied the PIO to generate the constrained gliding trajectory for hypersonic gliding vehicles. In this paper, to enhance the swarm populations' diversity of PIO, heterogeneous comprehensive learning (HCL) [31] strategy would be incorporated into PIO (HCLPIO), whose swarm populations are divided into two subpopulations for exploitation and exploration.

In this paper, the link-connected dynamic model is created for the HDS to describe the system's flexibility. The multi-wind disturbances consist of tanker trailing vortex, receiver bow wave, atmospheric turbulence, gust, and wind shear for simulating the real scene of AAR. Besides, the FOPID controllers optimized by HCLPIO are adopted to stabilize the drogue's relative position in the presence of multi-wind disturbances, which would make a significant impact on the success of AAR docking.

The remainder of this paper is organized as follows. The models of the HDS and multi-wind disturbances are described in Section 2. Then Section 3 specifies the heterogeneous comprehensive learning PIO algorithm. In Section 4, the optimized fractional-order feedback controllers are designed for stabilizing the drogue's relative position. Conclusions are contained in the final section.

2. Hose–drogue system and multi-wind disturbances environment

2.1. HDS components and coordinate system definition

The HDS contains three components: the hose, the controllable drogue, and the sensors. The hose–drogue assembly is described as a link-connected system based on the finite-segment multi-body method. In this way, the hose is divided into a certain number of links connected with frictionless joints where the aerodynamic forces and mass are concentrated according to the lumped parameter method. The controllable drogue (based on the work in [13]) is regarded as a mass point, and its aerodynamic forces could be controlled via changing the opening angles of actuators. Thus, the active-control aerodynamic forces are generated by the controllable drogue to resist the multi-wind disturbances. To simplify the model of HDS, the twist, elasticity, and damping are ignored. The hose–drogue assembly configuration and coordinate system definition are illustrated in Fig. 1.

As shown in Fig. 1, the dynamic model of the hose–drogue assembly is derived in the traction point coordinate system $O_d X_d Y_d Z_d$, whose x, y, z-axes are parallel to the tanker's trajectory coordinate $O_p X_p Y_p Z_p$. The inertial reference coordinate system is described as $O_g X_g Y_g Z_g$. The state angles of the k-th link $\boldsymbol{d}_k$ are presented as the angles $\vartheta_{k1}, \vartheta_{k2}$ respectively relative to the planes $O_d X_d Y_d$ and $O_d X_d Z_d$. The forces acting on the lumped mass k consist of hose tensions $\boldsymbol{T}_{k-1}, \boldsymbol{T}_k$, hose equivalent restoring force $\boldsymbol{R}_k$ [39], and resultant external force (the resultant force of gravity and aerodynamic forces). The controllable actuators on the drogue locate at the starboard brace (actuator 1), the port-side brace (actuator 3), the upper brace (actuator 2) aligned with the vertical, and the upper brace (actuator 4) aligned with the vertical.

2.2. Model of the HDS

The hose–drogue assembly is described as a link-connected system modeled via a finite-segment multi-body method [12,14]. To stabilize the drogue's relative position with multi-wind disturbances, the external forces of controllable drogue should be focused on.

The resultant external force $\boldsymbol{Q}_{dro}$ of controllable drogue can be expressed as [12]

$$\boldsymbol{Q}_{dro} = \left(\frac{m_N}{2} + m_{dro}\right)\boldsymbol{g} + \frac{\boldsymbol{D}_N}{2} + \boldsymbol{D}_{dro} \qquad (1)$$

where m_N, m_{dro} respectively denote the mass of the hose's N-th link and the drogue; $\boldsymbol{D}_N$ is the aerodynamic force of the hose's N-th link, which can be calculated as presented in [12, 14]; $\boldsymbol{D}_{dro}$ denotes the drag force of drogue. Besides the conventional drag force of drogue, the real active-control aerodynamic force $\boldsymbol{F}'_D$ is merged to $\boldsymbol{D}_{dro}$. As shown in Fig. 1, the four cruciform actuators [13] are controlled to change the opening angles $u_{act1}, u_{act2}, u_{act3}, u_{act4}$ of drogue's struct-braces (i.e., the red lines shown in Fig. 1). Thus, the controllable drogue can change its own drag force equivalent to generate the additional active-control aerodynamic forces for reducing the range of motion of the drogue's position. Specifically, according to the wind-tunnel test results [13], if decrease u_{act1} and increase u_{act3}, the drogue would generate a positive lateral force, and if decrease u_{act2} and increase u_{act4}, a positive vertical force would be generated. Therefore, $\boldsymbol{D}_{dro}$ can be calculated as

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