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Mixed adaptive control architecture for a novel coaxial-ducted-fan aircraft under time-varying uncertainties

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ARTICLE INFO

Article history:
Received 22 June 2017
Received in revised form 8 February 2018
Accepted 8 February 2018
Available online xxxx

Keywords:
Adaptive control
Model uncertainty
Ducted-fan aircraft

ABSTRACT

This paper is concerned with a kind of mixed adaptive control architecture for a novel tandem coaxial-ducted-fan aircraft in the presence of relative large time-vary uncertainties and external disturbances. For the proposed aircraft, elementary analysis is first performed to evaluate the system's inherent sensitivity to uncertainty. The control architecture includes mainly two parts: a robust decoupling controller and a L1 adaptive augmentation. The robust decoupling controller designed via H-infinity synthesis mainly provides states decoupling and ensures baseline performance; while the L1 adaptive augmentation based on L1 adaptive theory is mainly responsible for large uncertainty estimation and compensation. Numerical simulations of this novel unmanned aerial vehicle (UAV) are applied to illustrate the performances of the proposed control architecture. The simulation results reveal that compared to the classic robust method, the proposed controller is more effective and shows much improvement even under relative serious uncertainties and external disturbances.

1. Introduction

The UAVs have already become a currently focus both to common society as well as academic institution. On the one hand, the rapid developed autonomous flight control technology makes UAVs more easy and reliable to operate (both for inexperienced people and industrial communities); on the other hand, the great performance (such as effectiveness and convenience) makes UAVs suitable to support some advanced researches. Until now, most of the great UAVs are designed as open-rotor structure. However this dominant design may not satisfy the current requirements. The working environment and conditions are becoming more and more challenging. For example, people may require UAVs to enter inside rooms or other complicated indoor conditions instead of just working in open-air situation. Then, the inherent limitation of the traditional open-rotor UAVs will surely become an obstacle to their further practical application.

In order to improve practical performance, the ducted fan UAV (which is a novel aircraft structure) is driving evident interest in academic and industrial communities. Compared with the conventional open-rotor UAV, the duct UAV has many inherent advantages. These advantages enable duct UAV to achieve various applications on conditions that are unknown, complex, dangerous and inaccessible to traditional open-rotor aircrafts. Besides the obvious improvement of flight safety, a ducted-fan structure brings extra thrust than open-rotor in the same blade size. This main characteristic enable a markedly compact body design with strong mobility as well as high-efficiency [1,2].

In previous research of Beijing Institute of Technology (BIT), several prototypes of ducted fan aircraft have been designed for research such as system modeling, system identification as well as autonomous flight control algorithms [3–5]. Fig. 1 shows three of these design iterations and describes the different control moment generation mechanisms of them. The first prototype is proved to reveal poor stability and controllability due to its inefficiency actuator structure [6]. The second prototype improve the design of the actuator, however the new structure lead to heavily coupling which is still a serious challenge for aircraft control [3]. Under this context, the latest prototype is designed adopts two ducts with coaxial rotors and control vanes. Compared to the previous two prototypes, the latest structure is able to achieve much better decoupling features and controllability. What's more, the strong and axial flow from the duct enable control vane groups provide more control moment in roll direction.

The proposed novel UAV is a complex system without doubts. Unfortunately, the environment and working conditions make it an even more serious challenge for control system design. Through flight controller design there are several unavoidable situations: 1) the great matched uncertainties caused by model errors,

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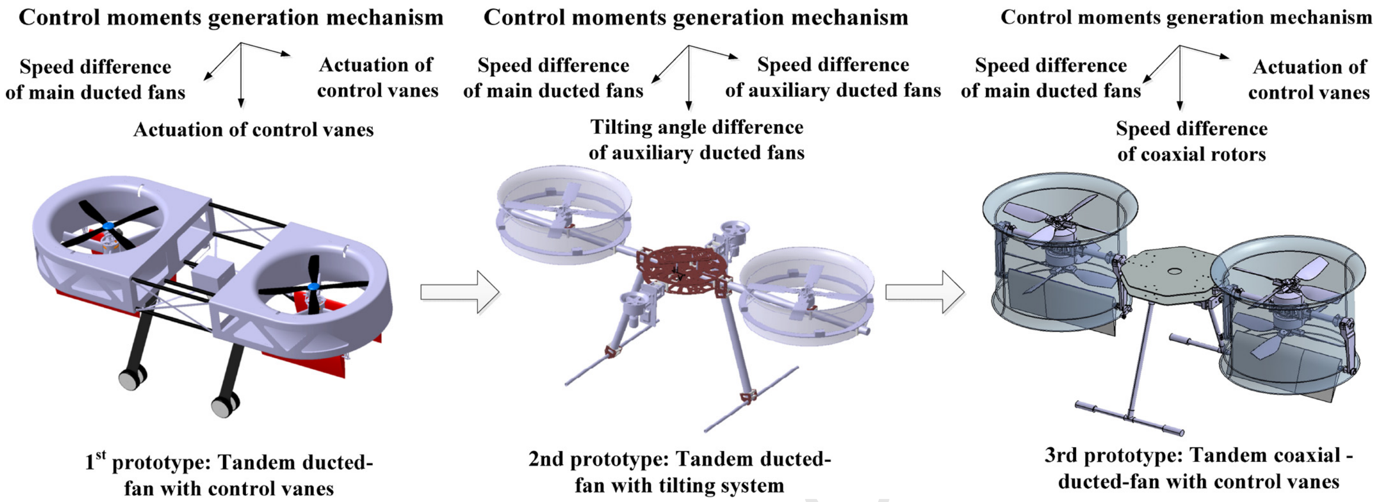
https://doi.org/10.1016/j.ast.2018.02.013

Please cite this article in press as: W. Fan et al., Mixed adaptive control architecture for a novel coaxial-ducted-fan aircraft under time-varying uncertainties, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.02.013



1st prototype: Tandem ducted-fan with control vanes

2nd prototype: Tandem ducted-fan with tilting system

3rd prototype: Tandem coaxial -ducted-fan with control vanes

Fig. 1. The illustration of previous design iterations in BIT.

un-modeled dynamics or input disturbances; 2) the great structure uncertainties caused by the unconventional working conditions; and 3) the great unknown external disturbances caused by wind or other special aerodynamic environment. The aim of this research is to design an effective controller to ensure relative good performance in the presence of these proposed time-varying uncertainties and external disturbances.

For the stable controller design of a multiple input multiple output (MIMO) ducted-fan aircraft, the classic PID method contributes a lot in [7], however this controller is not robust to uncertainties and disturbances which will lead to failure to full envelop flight. Dynamic inversion theory, sliding model control theory and neural control theory are respectively presented in [8–10] to provide rejection against external disturbances, however the performances of these control theories relay a lot on accurate system models. In order to achieve good performance with uncertainties, classic robust control theory based on H-infinity synthesis is proposed and studied. An effective two-loops robust control architecture is designed and employed in our previous team work [5]. The control architecture is able to provide good robust stabilization, however the performance drops when relative large uncertainties and disturbances are taken into consideration. A novel L1 adaptive control theory proposed by Pro. Naira Hovakimyan and Pro. Chengyu Cao in [11] provides an output-feedback adaptive control architecture for large uncertainty estimation and compensation. Compared to traditional adaptive control structure, this architecture has guaranteed transient performance and guaranteed robustness in the presence of fast adaption, without introducing or enforcing persistence of excitation, without any gain scheduling in the controller parameters, and without resorting to high-gain feedback. These features of the theory have been verified in many flight tests (detailed in [12–14]). Unfortunately, the research of this advanced adaptive structure is only studied at stable single input single output (SISO) system [11], which means that it cannot be applied to open-loop unstable MIMO systems directly.

In order to achieve robustness and transient performance for an open-loop unstable MIMO system in the presence of large uncertainties and external disturbances, a mixed-structure control architecture is proposed and detailed in this research. Considering the baseline performance, a structured robust controller tuned by non-smooth optimization method (proposed in [15]) via H-infinity synthesis is employed, which provides inner-loop input and output decoupling. Further, the output-feedback L1 adaptive augmentation is employed for each well decoupled state channels and ensures improvements in the presence of large time-varying uncertainties and external disturbances. The system uncertainty performs a key aspect through controller design. Therefore, before controller design, we present some elementary measures to analyze the system sensitivity to uncertainties which depending on the plant only.

The rest parts of this paper are organized as follows. Section 2 provides a brief introduction of the system dynamic model and presents some inherent sensitivity analysis to the plant uncertainties; the mixed-structure control architecture including robust decoupling controller and L1 adaptive augmentation is detailed in section 3; section 4 shows some simulation results and improvements of the closed-loop system employed with the proposed control architecture; and finally some summaries and conclusions are draw in section 5.

2. Introduction of system modeling and uncertainty analysis

2.1. Dynamic modeling

An efficient automatic flight control system design is always supported by an accurate plant model. Therefore, it's a critical work to set up a comprehensive dynamic model for research object. The dynamics description of the proposed UAV can be divided into four parts: 1) Rigid-body dynamics derived in body-fixed coordinate frame related to vehicle mass and inertias; 2) Aerodynamics which explain the force and moment generation mechanism for driving and controlling; 3) Actuator dynamics which offer maps from actuators to plant inputs; and 4) Model uncertainties and disturbances presented as time-varying perturbations or external forces and moments. In our previous team work, the rigid-body dynamics and actuator dynamics are presented in [16]. However, due to the duct effect and the coupling aerodynamics between the coaxial-rotors, it's a challenging task for accurate forces and moments derivation. In some researches, the duct effect is simplified as a force augmentation coefficient. In research [3,16,17], an inflow model is introduced to describe the duct effect. However this inflow model only aimed at single ducted rotor, it cannot evaluate the aerodynamics interference between coaxial rotors or interference between rotors and vanes. In research [18], the author discussed the proposed aerodynamic interference of a conventional open coaxial-rotor. But the additional duct in our case may have a significant effect on the flow field of the system and lead to a significant change in slipstream. In order to describe the model more precisely, the flow-field and aerodynamic characteristics are simulated and analyzed based on CFD method. Meanwhile, the effects of aero-interaction of ducts and rotors are also studied. Alignment of these simulation results with their experiment results can give some main aerodynamic parameters displayed in Fig. 2.

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