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[Aerospace Science and Technology](https://doi.org/10.1016/j.ast.2018.02.013) ••• (••••) •••-•••

Contents lists available at [ScienceDirect](http://www.ScienceDirect.com/) 1 67

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11 Mivod adaptive control architecture for a povel coavial ducted fan $\frac{11}{12}$ Mixed adaptive control architecture for a novel coaxial-ducted-fan $\frac{77}{78}$ ¹³ aircraft under time-varying uncertainties **are all the control of t**

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20 and the contract of the con A R T I C L E I N F O A B S T R A C T

22 88 *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

21 ANIILLE INFO ADSINALI

23 Article his paper is concerned with a kind of mixed adaptive control architecture for a novel tandem coaxial-
Passius 2017 24 Received in revised form 8 February 2018 For the proposed aircraft, elementary analysis is first performed to evaluate the system's inherent $\frac{90}{24}$ 25 Accepted 8 February 2018
sensitivity to uncertainty. The control architecture includes mainly two parts: a robust decoupling ⁹² ^{Available online xxxx} states and a Controller and a L1 adaptive augmentation. The robust decoupling controller designed via H-infinity ⁹² 27 **Forwards** Synthesis mainly provides states decoupling and ensures baseline performance; while the L1 adaptive ²⁸ Adaptive control augmentation based on L1 adaptive theory is mainly responsible for large uncertainty estimation and ⁹⁴ ²⁹ Model uncertainty and the state of the compensation. Numerical simulations of this novel unmanned aerial vehicle (UAV) are applied to illustrate ⁹⁵ 30 96 the performances of the proposed control architecture. The simulation results reveal that compared to 31 97 the classic robust method, the proposed controller is more effective and shows much improvement even 32 **18 met construct to the Construction Construction** and external disturbances. ducted-fan aircraft in the presence of relative large time-vary uncertainties and external disturbances.

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1. Introduction

 $_{40}$ The UAVs have already become a currently focus both to com-
 $_{40}$ $_{41}$ mon society as well as academic institution. On the one hand, instice that a markedly compact body design with strong mobility $_{107}$ $_{42}$ the rapid developed autonomous flight control technology makes as well as high-efficiency [1,2]. $_{43}$ UAVs more easy and reliable to operate (both for inexperienced and the previous research of Beijing institute of Technology (BIT), $_{108}$ $_{44}$ people and industrial communities); on the other hand, the great several prototypes of ducted fan aircraft have been designed for $_{110}$ $_{45}$ performance (such as effectiveness and convenience) makes UAVs research such as system modeling, system identification as well as $_{111}$ $_{46}$ suitable to support some advanced researches. Until now, most of autonomous flight control algorithms [3-5]. Fig. 1 shows three of $_{112}$ $_{47}$ the great UAVs are designed as open-rotor structure. However this these design iterations and describes the different control moment 1_{13} $_{48}$ dominant design may not satisfy the current requirements. The generation mechanisms of them. The first prototype is proved to $_{\rm 114}$ $_{49}$ working environment and conditions are becoming more and more are reveal poor stability and controllability due to its inefficiency ac- $_{50}$ challenging. For example, people may require UAVs to enter in-cluator structure [6]. The second prototype improve the design of $_{\rm 116}$ $_{51}$ side rooms or other complicated indoor conditions instead of just the actuator, however the new structure lead to heavily coupling $_{117}$ $_{52}$ working in open-air situation. Then, the inherent limitation of the which is still a serious challenge for aircraft control [3]. Under this 1_{16} $_{53}$ traditional open-rotor UAVs will surely become an obstacle to their context, the latest prototype is designed adopts two ducts with $_{119}$ further practical application.

₅₅ In order to improve practical performance, the ducted fan UAV prototypes, the latest structure is able to achieve much better de- $_{56}$ (which is a novel aircraft structure) is driving evident interest in coupling features and controllability. What's more, the strong and $_{122}$ $_{57}$ academic and industrial communities. Compared with the conven- axial flow from the duct enable control vane groups provide more $_{123}$ $_{58}$ tional open-rotor UAV, the duct UAV has many inherent advan-control moment in roll direction. In order to improve practical performance, the ducted fan UAV

64 130 <https://doi.org/10.1016/j.ast.2018.02.013>

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 $\frac{37}{100}$ 1. Introduction **inaccessible to traditional open-rotor aircrafts**. Besides the obvious ³⁸ ¹⁰⁴ improvement of flight safety, a ducted-fan structure brings extra 39 105 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 [\[1,2\]](#page--1-0).

 54 further practical application. 54 coaxial rotors and control vanes. Compared to the previous two 120 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 [\[3–5\]](#page--1-0). Fig. [1](#page-1-0) 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 [\[6\]](#page--1-0). 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 [\[3\]](#page--1-0). Under this context, the latest prototype is designed adopts two ducts with coupling 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.

 $_{59}$ tages. These advantages enable duct UAV to achieve various appli- The proposed novel UAV is a complex system without doubts. $_{125}$ $_{60}$ cations on conditions that are unknown, complex, dangerous and Unfortunately, the environment and working conditions make $_{126}$ 61 127 it an even more serious challenge for control system design. 62 128 Through flight controller design there are several unavoidable situ-63 **63** *E-mail address: fanweixx@gmail.com* (W. Fan). The stromations: 1) the great matched uncertainties caused by model errors, 129 The proposed novel UAV is a complex system without doubts. Unfortunately, the environment and working conditions make

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 $\frac{22}{100}$ uncertainties caused by the unconventional working conditions; sign, we present some elementary measures to analyze the system $\frac{88}{100}$ ²³ and 3) the great unknown external disturbances caused by wind sensitivity to uncertainties which depending on the plant only. $\frac{24}{25}$ or other special aerodynamic environment. The aim of this re-
 $\frac{24}{25}$ or other special aerodynamic environment. The aim of this re-
 $\frac{24}{25}$ The rest parts of this paper are organized as follows. Sectio ²⁵ search is to design an effective controller to ensure relative good provides a brief introduction of the system dynamic model and $\frac{91}{20}$ $\frac{26}{2}$ performance in the presence of these proposed time-varying un-
certainties and external disturbances.

29 95 output (MIMO) ducted-fan aircraft, the classic PID method con-³⁰ tributes a lot in [7], however this controller is not robust to uncer-
example of the closed-loop system employed with the proposed con-³¹ tainties and disturbances which will lead to failure to full envelop trol architecture; and finally some summaries and conclusions are $\frac{97}{100}$ ³² flight. Dynamic inversion theory, sliding model control theory and draw in section 5. 33 neural control theory are respectively presented in $[8-10]$ to pro- $\frac{34}{100}$ vide rejection against external disturbances, however the perfor-**2. Introduction of system modeling and uncertainty analysis** 35 101 mances of these control theories relay a lot on accurate system 36 models. In order to achieve good performance with uncertain- 2.1. Dynamic modeling 37 ties, classic robust control theory based on H-infinity synthesis is 103 tributes a lot in [\[7\]](#page--1-0), however this controller is not robust to uncerproposed and studied. An effective two-loops robust control architecture is designed and employed in our previous team work [\[5\]](#page--1-0). 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 sation. 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 applied to open-loop unstable MIMO systems directly.

In order to achieve robustness and transient performance for certainties and external disturbances, a mixed-structure control arnon-smooth optimization method (proposed in [\[15\]](#page--1-0)) via H-infinity

²¹ un-modeled dynamics or input disturbances; 2) the great structure aspect through controller design. Therefore, before controller deaspect 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.

 $\frac{27}{2}$ certainties and external disturbances. ²⁸ For the stable controller design of a multiple input multiple decoupling controller and L1 adaptive augmentation is detailed in 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 uncerdecoupling controller and L1 adaptive augmentation is detailed in section [3;](#page--1-0) section [4](#page--1-0) shows some simulation results and improvetrol architecture; and finally some summaries and conclusions are draw in section [5.](#page--1-0)

2. Introduction of system modeling and uncertainty analysis

2.1. Dynamic modeling

 38 proposed and studied. An effective two-loops robust control archi-
An efficient automatic flight control system design is always 104 ³⁹ tecture is designed and employed in our previous team work [5]. Supported by an accurate plant model. Therefore, it's a critical 105 ⁴⁰ The control architecture is able to provide good robust stabiliza-
work to set up a comprehensive dynamic model for research ob-⁴¹ tion, however the performance drops when relative large uncer-
 μ ject. The dynamics description of the proposed UAV can be divided by 107 ⁴² tainties and disturbances are taken into consideration. A novel L1 into four parts: 1) Rigid-body dynamics derived in body-fixed coor-⁴³ adaptive control theory proposed by Pro. Naira Hovakimyan and dinate frame related to vehicle mass and inertias; 2) Aerodynamics 108 ⁴⁴ Pro. Chengyu Cao in [\[11\]](#page--1-0) provides an output-feedback adaptive which explain the force and moment generation mechanism for ¹¹⁰ ⁴⁵ control architecture for large uncertainty estimation and compen-
⁴⁵ control architecture for large uncertainty estimation and compen-
divided riving and controlling; 3) Actuator dynamics which effer maps ⁴⁶ sation. Compared to traditional adaptive control structure, this ar-

from actuators to plant inputs; and 4) Model uncertainties and 112 47 chitecture has guaranteed transient performance and guaranteed disturbances presented as time-varying perturbations or external 113 ⁴⁸ robustness in the presence of fast adaption, without introducing forces and moments. In our previous team work, the rigid-body 114 ⁴⁹ or enforcing persistence of excitation, without any gain scheduling dynamics and actuator dynamics are presented in [\[16\]](#page--1-0). However, ¹¹⁵ 50 in the controller parameters, and without resorting to high-gain due to the duct effect and the coupling aerodynamics between 116 ⁵¹ feedback. These features of the theory have been verified in many the coaxial-rotors, it's a challenging task for accurate forces and ¹¹⁷ 52 flight tests (detailed in [12–14]). Unfortunately, the research of this moments derivation. In some researches, the duct effect is sim-
 ⁵³ advanced adaptive structure is only studied at stable single input plified as a force augmentation coefficient. In research [3,16,17], ¹¹⁹ 54 single output (SISO) system [\[11\]](#page--1-0), which means that it cannot be an inflow model is introduced to describe the duct effect. How- 120 ⁵⁵ applied to open-loop unstable MIMO systems directly. extermal over this inflow model only aimed at single ducted rotor, it cannot ¹²¹ 56 In order to achieve robustness and transient performance for evaluate the aerodynamics interference between coaxial rotors or 122 57 an open-loop unstable MIMO system in the presence of large un-
interference between rotors and vanes. In research [18], the author 123 58 certainties and external disturbances, a mixed-structure control ar-
 68 discussed the proposed aerodynamic interference of a conventional 124 59 chitecture is proposed and detailed in this research. Considering open coaxial-rotor. But the additional duct in our case may have a 125 60 the baseline performance, a structured robust controller tuned by significant effect on the flow field of the system and lead to a sig- 126 ⁶¹ non-smooth optimization method (proposed in [15]) via H-infinity aificant change in slipstream. In order to describe the model more 127 62 synthesis is employed, which provides inner-loop input and output precisely, the flow-field and aerodynamic characteristics are simu- 128 63 decoupling. Further, the output-feedback L1 adaptive augmentation lated and analyzed based on CFD method. Meanwhile, the effects 129 64 is employed for each well decoupled state channels and ensures of aero-interaction of ducts and rotors are also studied. Alignment 130 65 improvements in the presence of large time-varying uncertainties of these simulation results with their experiment results can give 131 ⁶⁶ and external disturbances. The system uncertainty performs a key some main aerodynamic parameters displayed in Fig. 2. $\frac{132}{2}$ which explain the force and moment generation mechanism for driving and controlling; 3) Actuator dynamics which offer maps plified as a force augmentation coefficient. In research [\[3,16,17\]](#page--1-0), an inflow model is introduced to describe the duct effect. Howinterference between rotors and vanes. In research [\[18\]](#page--1-0), the author 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 sigprecisely, 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.](#page--1-0)

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