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Differential geometry based active fault tolerant control for aircraft ☆

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ABSTRACT

This work shows how to use a differential geometry tool to design a novel nonlinear active fault tolerant flight control system for aircraft. The proposed control scheme consists of two main subsystems: a controller, which is designed for the nominal plant, and a fault detection and diagnosis module, which provides fault estimation. A further feedback loop exploits the fault estimation to accommodate faults affecting the system. The estimate convergence and the stability of the active fault tolerant flight controller are theoretically proved. Finally, high fidelity simulations show the effectiveness of the scheme.

1. Introduction

A conventional feedback control design for a complex system may lead to unsatisfactory performance, or even instability, in the event of malfunctions affecting actuators, sensors or other system components. This is particularly important for safety-critical systems, such as aircraft applications. In these cases, the effect of a minor fault in a system component, in particular the actuators, can lead to catastrophic consequences.

To overcome these drawbacks, fault tolerant control (FTC) systems have been developed in order to tolerate component malfunctions, while maintaining desirable stability, and performance properties.

In general, FTC methods are classified into two types, *i.e.* passive fault tolerant control (PFTC), and active fault tolerant control (AFTC) schemes (Blanke, Kinnaert, Lunze, & Staroswiecki, 2006; Mahmoud, Jiang, & Zhang, 2003; Zhang & Jiang, 2008). In PFTC systems, controllers are fixed, and designed to be robust against a class of presumed faults. This approach, which offers only limited fault-tolerant capabilities, does not need any fault estimate (or detection) or controller reconfiguration. In contrast to PFTC, AFTC systems react to the faults actively by reconfiguring the control actions, so that the stability and acceptable performance of the entire system can be maintained. AFTC schemes rely heavily on real-time fault detection and diagnosis (FDD) schemes, which are exploited for providing the most up-to-date information about the true status of the system. Usually, this information can be used from a logic-based switching controller or a feedback of the fault estimate. The approach proposed in this paper relies on the latter strategy.

Over the last three decades many FDD techniques have been developed, see the survey works (Benini, Castaldi, & Simani, 2009; Ding, 2008; Isermann, 2005; Simani, Fantuzzi, & Patton, 2003; Theilliol, Join, & Zhang, 2008; Witczak, 2007). Regarding the AFTC system design, it was argued that effective FDD is needed (Mahmoud et al., 2003; Zhang & Jiang, 2008). Moreover, it was claimed that, for the system to react properly to a fault, timely and accurate detection and location of the fault itself are needed. Fault detection and isolation (FDI) is the area where research studies have mostly been explored. On the other hand, FDD schemes represent a challenging topic because they have to provide also the fault estimate. FDI and FDD schemes usually exploit dynamic observers or filters. Unfortunately, disturbance affecting the system can cause false alarms or, even worse, missed faults. Robustness issues in FDI and FDD are therefore very important (Blanke et al., 2006; Chen & Patton, 1999; Isermann, 2005; Witczak, 2007).

This paper presents an innovative differential geometry application together with a novel non-linear geometric approach (NLGA) results in the field of AFTC for aerospace systems. For the first time the standard NLGA procedure presented in Persis and

Abbreviations: AFTC, active fault tolerant control; FDD, fault detection and diagnosis; FDI, fault detection and isolation; NLGA, non-linear geometric approach; AF, adaptive filters

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Isidori (2001) has been extended to the input fault scenario in the presence of fault estimation feedback.

In particular the applied AFTC is based on an extended version of the FDD module, designed in Castaldi, Geri, Bonfè, Simani, and Benini (2010) for the case of sensor faults.

It is worth observing that in Castaldi et al. (2010) the FDD module is used only for fault estimate and the fault feedback is not present, as for the case of the proposed AFTC system. For this reason new proofs, given in the following, are provided to assess the convergence of the fault estimate to the actual fault.

The filter structure is derived using the coordinate change of the NLGA theory developed in Persis and Isidori (2001), which is only the starting point for the filter design. The application of the NLGA to the aircraft longitudinal model is investigated, in order to obtain fault estimates decoupled from disturbance and/or other faults. In this paper the actuator fault estimation is accomplished by adaptive filters (AF) which, designed by using the NLGA, are analytically decoupled from relevant wind components. For the case of the design of the FDI module *via* the NLGA, see the paper by Bonfè, Castaldi, Geri, and Simani (2007).

The fault estimates provided by the proposed NLGA–adaptive filters (NLGA–AF) are unbiased *via* the above-mentioned disturbance decoupling. It is worth observing that the adaptive filters not using the proposed NLGA procedure are not decoupled from disturbances and/or other fault. The proposed FDD module thus increases the reliability of the overall AFTC system. Note that the problem of the exact decoupling of disturbance and other faults, proposed in this paper, has not been solved previously by other authors.

Moreover it is important to observe that also the design of the control systems proposed in this work is based on differential geometry tools. The suggested controller presents novel issues with respect to other schemes relying on differential geometry already present in the related literature. With reference to the paper by Castaldi, Mimmo, and Simani (2011) the design of the controller has been completely modified and based on the differential geometry approach. This provides a novel controller that allows us to achieve the stability of the overall AFTC system. In particular, the novel controller has been designed by exploiting some concepts from two well known theoretic tools: exact feedback linearization (Isidori, 1995) and singular perturbation (Khalil, 2002). In particular, starting from the proposed aircraft model, proper controllers are designed *via* the exact feedback linearization tool, and assuming suitable virtual control inputs. In this way, the complete system is linear, and exponentially stabilizable.

The overall AFTC scheme, consisting of the proposed controller and the fault accommodation method, shows several interesting properties. To the best of the authors′ knowledge, the designed controller, the FDD modules, and the whole scheme represent innovative results.

Finally, the novel aircraft AFTC system, based on the differential geometry tool and the NLGA, has been tested on a high-fidelity simulator. It implements realistic disturbance, such as sensor measurement noise and wind, thus showing the effectiveness and the good performance of the proposed AFTCS.

The paper is organized as follows.

Section 2 describes the structure of the proposed AFTC: the theoretical and practical design of the NLGA–AF, the estimation properties and convergence proof are given in Section 2.1; Section 2.3 presents the controller design process and its stability proof. The overall AFTCS stability proof is given in Section 2.4.

Section 3 provides more details regarding the simulator, while Section 4 shows the effectiveness and robustness of the AFTC aerospace system by means of extensive simulations.

Concluding remarks are drawn in Section 5. All symbols and equations used in this paper to describe the aircraft model have been listed in Appendix A.

2. Differential geometry based AFTC

Fig. 1 describes the adopted structure of the AFTC scheme where $\mathbf{u}$ is the controller output, $\mathbf{x}$ is the state vector, $\mathbf{y}$ and $\mathbf{y}_{ref}$ are the measured and the reference output vectors, respectively. The vector $\mathbf{f}$ is the actuator fault, while $\hat{\mathbf{f}}$ is the estimated actuator fault. Therefore, Fig. 1 shows that the AFTC strategy is obtained by integrating the FDD module with the control system. The FDD module, consisting of a bank of NLGA–AFs, provides the correct estimation $\hat{\mathbf{f}}$ of the actuator fault $\mathbf{f}$, as it will be proved in Theorem 1. This estimated signal is injected into the control loop in order to compensate the effect of the actuator fault. Thanks to this fault estimation feedback the controller can be easily designed considering the fault-free plant (Fig. 2).

2.1. NLGA–AF based FDD module

This section describes the implementation of the FDD module. It is proved that the fault estimation provided by NLGA–AF and exploited in the overall AFTC scheme is unbiased. Note that in the works by the same authors Bonfè, Castaldi, Geri, and Simani (2006, 2007) and Castaldi et al. (2010) related to the FDI scheme design, the fault estimate does not depend on the fault estimate itself due to the further feedback loop. Moreover, in Castaldi et al. (2011) the proof of convergence of the fault estimation was left as an open problem here formally solved for the first time. Finally some interesting properties related to the dynamics of the estimation error are given.

The FDD module is based on the NLGA approach, where a coordinate transformation highlights a sub-system affected by the fault and decoupled by the disturbances. This subsystem is the starting point to design a set of adaptive filters. They are able to both detect additive fault acting on a single actuator and estimate the magnitude of the fault itself. The proposed approach can be properly applied to the nonlinear affine model of the system in the form:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{n}(\mathbf{x}) + \mathbf{g}(\mathbf{x})(\mathbf{u} - \hat{\mathbf{f}} + \mathbf{f}) + \mathbf{p}_d(\mathbf{x})\mathbf{d} \\ \mathbf{y} = \mathbf{h}(\mathbf{x}) \end{cases} \tag{1}$$

where $\mathbf{x} \in \mathcal{X}$ (an open subset of $\mathbb{R}^{\ell_n}$) is the state vector, $\mathbf{u}(\mathbf{t}) \in \mathbb{R}^{\ell_c}$ is the control input vector, $\mathbf{f}(\mathbf{t})$ and $\hat{\mathbf{f}}(t) \in \mathbb{R}^{\ell_f}$ are the fault vector and its estimate, respectively. The vector $\mathbf{d}(t) \in \mathbb{R}^{\ell_d}$ is the disturbance vector (including also the faults which have to be decoupled, in order to perform the fault isolation) and $\mathbf{y} \in \mathbb{R}^{\ell_m}$ is the output vector, while $\mathbf{n}(\mathbf{x})$, the columns of $\mathbf{g}(\mathbf{x})$, and $\mathbf{p}_d(\mathbf{x})$ are smooth

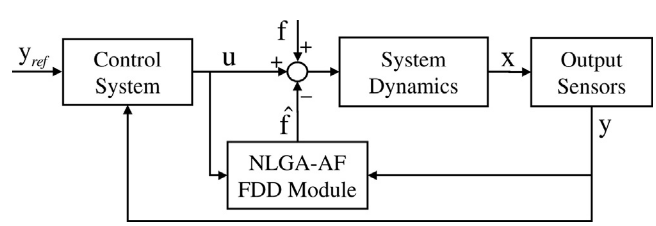

Fig. 1. Logic diagram of the integrated AFTC strategy.

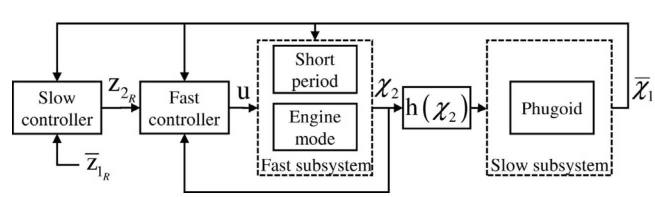

Fig. 2. Altitude and airspeed controller.