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Combining sensor monitoring and fault tolerant control to maintain flight control system functionalities

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Abstract: To maintain nominal flight control system functionalities during fault scenarios, enhancements of the state-of-practise angle of attack and airspeed sensor fault accommodation strategies are presented. The strategy combines a fault detection and diagnosis (FDD) system with a robust fault tolerant control law. The FDD system allows to maintain the nominal flight control law as long as at least one angle of attack and airspeed sensor are available. The FDD system is designed using advanced nullspace computation, optimization, and signal processing techniques. For the scenario of a total airspeed measurement loss, an airspeed independent longitudinal backup control law is designed using global optimization techniques. Using this law avoids the state-of-practise switch to a direct law in which the pilot must control the elevator positions directly. The results from an extensive industrial validation and verification campaign are reported.

Keywords: Fault tolerant flight control, fault detection & isolation, verification and validation.

1. INTRODUCTION

Fault detection and diagnosis (FDD) as well as fault tolerant control (FTC) approaches were pragmatically pursued to establish a maximum degree of safety and reliability. For the new generation of aircraft this pragmatic design paradigm has been raised to a performance-oriented one which can be termed as full-time and all-event availability of performance-optimized guidance, navigation and control (GNC) functions Goupil et al. (2015). Such a robust provision of GNC functions can be translated in the desire to assist the pilot in all possible scenarios to keep the flight safe, making the flight task itself easier and the mission optimal. A high level description of this idea is given in Figure 1. In fault scenarios, which are indicated by the red dots in the figure, it may be necessary to downgrade to a control law with less GNC functionality. This can be, for example, due to the unavailability of a certain sensor signal or actuator. Such a degradation is referred to moving from the *normal law*, i.e. nominal functionality, to an *alternate law*, providing limited functionality. In the worst case scenario, the pilot will fly the so called *direct law*, where the pilot directly controls the control surface of the aircraft. The flight in the direct law shall be avoided, as in this law the pilot has to focus most of the attention on the piloting task. Thus, current FDD/FTC research is focused on the situational extension of the nominal GNC functionality level in case of faults. This is illustrated by moving the purple line (current situation) of degradation to the right (desired situation).

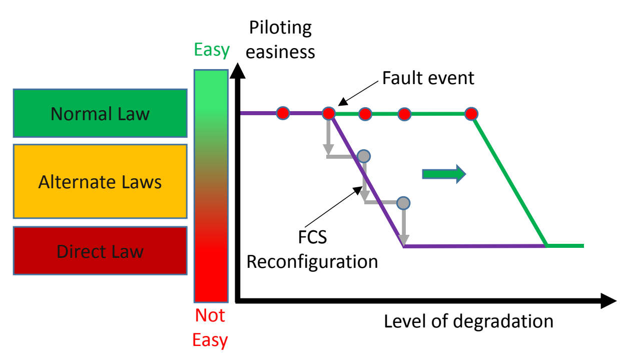

Fig. 1. Illustration of GNC functionality extension idea

To achieve high GNC functionality in case of faults, the key enablers have been identified to be advanced FDD and FTC, which can contribute to the future more sustainable aircraft Goupil et al. (2015). Early and robust detection of incipient faults thanks to advanced FDD is required to extend the availability of key flight parameters and thereby *maintain* the nominal GNC functionality level. In case of a loss of key flight parameters FTC allows to *improve* the flight control system (FCS) functionality to get closer to its nominal level. Two key flight parameters required to ensure the highest possible FCS functionality level is the aircraft's angle of attack (AoA) and its calibrated airspeed (VCAS). While the latter is used to schedule the

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control gains and thus highly influences the performance and stability of the aircraft, the first is used to protect the aircraft from reaching stall conditions. Due to their importance for the FCS, we propose two main algorithms to enhance the state-of-practice VCAS and AoA sensor fault accommodation strategy: an advanced FDD system to monitor the triplex redundant VCAS and AoA measurements as well as an alternate longitudinal control law, a so-called backup law, independent of the two measurements.

The advanced FDD system enhances current state-of-practice to be able to isolate multiple sensor faults. The state-of-practice monitoring scheme is able to cope with a single fault scenario in the triplex redundant measurement system Berdjag et al. (2013) and switches to an alternate or even direct law in case of more than one fault. The presented FDD system allows maintaining the normal law, i.e. the nominal longitudinal control law and all protections, as long as one sensor in each of the two triplex redundant measurements is still working . In case of a total loss of the VCAS measurements the state-of-practice fault accommodation strategy initiates a switch to the direct law, where the pilot directly controls the elevators via his stick actions. For this scenario a newly developed backup law is presented. This backup law operates the aircraft without using VCAS for scheduling and keeps the stability and performance level close to the normal law.

The tackled problem is part of the EU-FP7 RECONFIGURE project on FDD/FTC techniques for modern civil aircraft. Valuable contributions dealing with the same or parts of the defined problem can be found in literature: In Rosa et al. (2015) a mixed-μ FDD/FTC approach is proposed, in Hardier et al. (2015) an online parameter estimation algorithm to recover lost measurements is applied, in Wan et al. (2016) a moving horizon estimation techniques for the FDD problem is used, in Chen et al. (2015) sliding mode observers to tackle the sensor FDD problem are developed, and in Hartley and Maciejowski (2015) a fault tolerant longitudinal law based on model predictive control is presented. In the approach in this paper the combined FDD/FTC problem is tacked. The use of signal together with model based fault detection techniques as well as the use of global optimization techniques differentiates the presented approach from the mentioned contributions. These techniques allow the design of an FDD/FTC system with increased performance. To show this, the final part of the paper deals with the reporting of the latest results of an extensive industrial validation and verification campaign set up in the RECONFIGURE project.

2. FAULT ACCOMMODATION STRATEGY

Up to three AoA and three VCAS faults result in various different fault scenarios to be dealt with. In this section a summary of the strategy coping with these scenarios is given. In Table 1 possible fault scenarios and its accommodation strategies are listed. As long as one of the AoA *and* VCAS sensors are properly working, the nominal control law together with its full protection functionality can be maintained. This extends the state of practice capability, which can only deal with a single sensor in every triplex redundant measurement.

In case of a total loss of the AoA sensors, an alternate law, namely the nominal control law without direct AoA protections is activated. This alternate law is state of practice and should not be confused with the herein developed backup law. The backup law, independent of VCAS, is activated in case of a total loss of the VCAS sensors. It provides satisfactory handling qualities and avoids the switch to the direct control law, but does not include direct AoA protections. This fault accommodation strategy is also coherent with another main design constraints, namely to keep the nominal control law and protections in operation as long as possible.

Scenario	**Running algorithms**
fault free	nominal control law and protections
1 or 2 AoA sensors fail	fault isolation and use of remaining AoA sensor to maintain nominal control law and protections
1 or 2 VCAS sensors fail	fault isolation and use of remaining VCAS sensor to maintain nominal control law and protections
3 AoA sensors fail	switch to alternate law which includes nominal control law but without direct AoA protections
3 VCAS sensors fail or all 6 sensors fail	switch to a VCAS independent longitudinal backup law

Table 1. Fault accommodation strategy

Note, in case of further or other failures, as for example the loss of the inertial measurement unit or the loss of flight control computers, it might still be necessary to the activate the direct law. However, the presented approach helps to extend the provision of high GNC functionality levels during VCAS and AoA faults.

3. FAULT DETECTION AND ISOLATION SYSTEM FOR ROBUSTLY MONITORING AOA AND VCAS

As the FDD system needs to be able to detect and isolate the faulty sensors, i.e. locate which sensors are faulty, each of the six air data sensors (three for AoA and three for VCAS) are monitored without the use of the other five sensors. In this way it is possible to avoid a coupling between the faults and directly solve the fault isolation problem. This is schematically shown for a triplex redundant sensor system in Fig. 2. Each of the

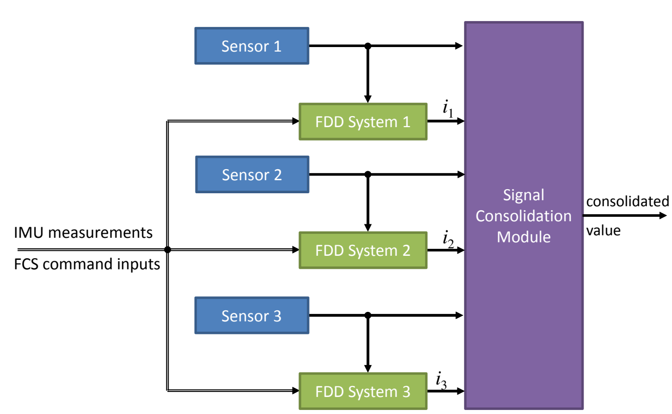

Fig. 2. FDD system monitoring a triplex sensor system

six fault detection subsystems consist of a model based