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Sensor fault detection and isolation for aircraft control systems by kinematic relations

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ABSTRACT

This paper presents a new approach to Fault Detection and Isolation (FDI) for sensors of aircraft. In the most general case, fault detection of these sensors on modern aircraft is performed by a logic that selects one of, or combines, the three redundant measurements. Such a method is compliant with current airworthiness regulations. However, in the framework of the global aircraft optimization for future and upcoming aircraft, it could be required, e.g., to extend the availability of sensor measurements. Introducing a form of analytical redundancy of these measurements can increase the fault detection performance and result in a weight saving of the aircraft. This can be achieved by exploiting the knowledge of the kinematic relations between the measured variables. These relations are exactly known giving the advantage that no model-mismatches need to be accounted for. Furthermore these relations are valid over the whole flight envelope and general for any type of aircraft. Two example applications will be presented, showing the applicability of the method for the FDI of air data sensors and measurements of the inertial reference unit.

1. Introduction

This paper presents a new approach to sensor Fault Detection and Isolation (FDI) for Electronic Flight Control System (EFCS) of aircraft. The approach was developed in the scope of the European FP7 project Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE), of which the goal was to research and develop Fault Detection and Diagnosis (FDD) methods for aircraft flight control systems, mainly sensor and actuator malfunctions (Goupil & Marcos, 2011). One of the main objectives of the project was the support of the development of greener aircraft, as will be explained in the next section. Furthermore, the ADDSAFE project aimed at closing the gap between the academic field of research of FDD and the practical application of these methods in industry.

1.1. Motivation for sensor FDI

One of the fault scenarios in ADDSAFE deals with Air Data and Inertial Reference System (ADIRS) monitoring, which consists of three Air Data and Inertial Reference Units (ADIRUs). The redundant measured signals available from the ADIRS are monitored and consolidated in the aircraft's Flight Control Computer (FCC) (Traverse, Lacaze, & Souyris, 2004; Favre, 1994). These measurements are used to determine the state of the aircraft and are compared with the control objectives, after which the FCC calculates the required control surface deflections through the flight control laws. An overview of a typical EFCS architecture is shown in Fig. 1. Faulty measurements which are fed back to the flight control laws can create unwanted control signals leading, e.g., to higher loads on the aircraft structure. For that reason, the aircraft structures are designed to withstand these unwanted loads up to a level at which it is guaranteed that the faults can be detected and appropriate actions can be taken. In the most general case, fault detection of these sensors on modern aircraft is performed by a monitoring process that selects one of, or combines, the three redundant measurements such that the EFCS and the control laws are provided with a correct measurement. This consolidation process can consist of a majority voting or a weighted mean method (Allerton & Jia, 2005). Other approaches can also include soft-computing algorithms (Oosterom, Babuska, & Verbruggen, 2002). A specific example is the so-called triplex scheme (Goupil, 2011).

However, for upcoming and future aircraft one important aspect is the structural design optimization. This can lead to a substantial decrease in the weight of the aircraft, which again leads to an increase in the aircraft's performance, including a decrease in fuel consumption, a decrease in produced noise and an increased range. Furthermore, these advantages also satisfy

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Abbreviations

FDD	Fault Detection and Diagnosis
EFCS	Electronic Flight Control System
ADS	Air Data Sensors
ADDSAFE	Advanced Fault Diagnosis for Sustainable Flight Guidance and Control
ADIRU	Air Data and Inertial Reference Unit
ADIRS	Air Data and Inertial Reference System
FDI	Fault Detection and Isolation
KF	Kalman Filter
EKF	Extended Kalman Filter
IRU	Inertial Reference Unit
MSE	Mean Square Error
NRZ	Non-Return to Zero
AOA	Angle-Of-Attack
PCA	Principal Component Analysis
IMU	Inertial Measurement Unit
FCC	Flight Control Computer
DTP	Detection Time Performance

the newer societal imperatives toward environmentally friendlier aircraft. Improving the FDD performance of the aircraft's EFCS allows to optimize the aircraft structural design and performance resulting in a lower operating cost and decreased environmental impact (Goupil & Marcos, 2012), as explained above. Another motivation for the development of analytical redundancy for aircraft parameter measurements is to extend the availability of the sensor measurements. Instead of adding one or several new sensors, the option of adding a *virtual* sensor, i.e. analytical redundancy, gives the advantage, no additional weight is required. This results again in the same advantages as described above. These two reasons indicate the need to create new advanced FDD methods and to close the gap between academic research and industrial application.

1.2. Antecedents and main contribution

There is a wide variety of methods available in the literature for adding analytical redundancy for sensor FDI in aerospace applications, as presented by Marzat, Piet-Lahanier, Damongeot, and Walter (2012). The different approaches include Luenberger observers, Kalman filters, particle filters, $\mathcal{H}_\infty$ filters, sliding mode observers, bounded-error observers, neural networks and support vector machines. For references to these methods the reader is referred to the overview given by Marzat et al. (2012), including a list of main advantages and disadvantages. A lot of these methods deal only with one specific fault, being a bias, a drift or an oscillatory fault and are based on a dynamic model of the aircraft.

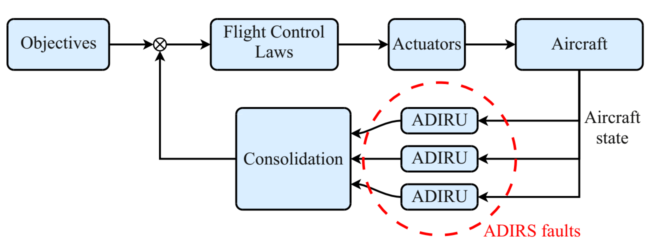

Fig. 1. Typical flight control architecture of an aircraft.

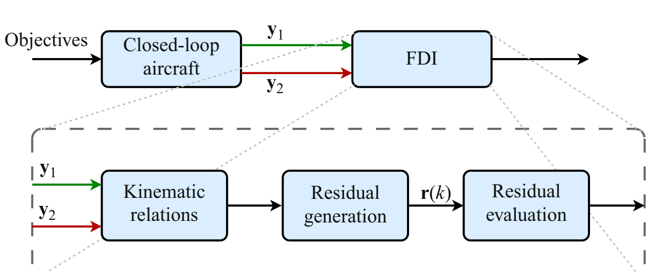

Fig. 2. FDI approach for the ADIRS monitoring.

Therefore, the methods need to deal with model inaccuracies, unknown disturbances and sometimes linearization of the nonlinear aircraft models. In the case when a dynamic model of the aircraft is absent, neural networks or Principal Component Analysis (PCA) can be used. However, these approaches need training data. Furthermore, learning convergence for neural networks is not guaranteed and PCA needs a linear dependence between the variables. An example of a model-free approach for sensor FDI is presented by Berdjag, Cieslak, and Zolghadri (2012) for the case of an oscillatory sensor fault.

In this paper a new approach to sensor FDI for aircraft is presented based on the kinematic relations between the different measured variables of the ADIRUs. The idea is to split the measurement vector into two parts. These two parts can then be checked for consistency through the kinematic relations. This idea is presented in Fig. 2.

The advantages of the kinematic relations for the purpose of sensor FDD have not been widely exploited according to Marzat et al. (2012). However, as these relations can be considered to be known exact, no model mismatches or unmodeled dynamics need to be taken into account, creating a big advantage over classical model based approaches. Furthermore, only limited knowledge about the specific aircraft is required. Additional advantages are the following:

1. The method developed is valid over the whole flight envelope of the aircraft. This means that no special measures need to be taken such as gain scheduling.
2. The method can be applied to any aircraft, without large modifications (except for the location of the sensors). So the developed method is general for aircraft.
3. The method is insensitive to other types of faults, e.g., actuator faults, control surface jamming, etc.

Two different applications will be presented which add analytical redundancy for the available measurements in the ADIRS. Both methods combine the knowledge of the kinematic relations between the measurements and the hardware redundancy which is available on modern aircraft to enhance the state of the art ADIRS monitoring performance.

The first application deals with FDI for Air Data Sensors (ADS), i.e., the airspeed, Angle-Of-Attack (AOA) and side-slip measurements. By applying an Extended Kalman Filter (EKF) a reduced state vector of the aircraft is estimated. The Mean Square Error (MSE) of the innovations of the monitored sensors is used as a performance metric for the sensors. The consolidation of the redundant measurements is then performed using this MSE and as such FDI is achieved. It should be noted that the FDI of the airspeed and side-slip measurement was not required by the ADDSAFE project. The second example shows how the kinematic relations can be used for the FDI of accelerometer and rotational rate measurements. In this case, the kinematic relations can be