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The challenge of advanced model-based FDIR for real-world flight-critical applications

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ABSTRACT

This paper aims at providing a brief perspective of advanced model-based Fault Detection, Identification and Recovery (FDIR) for aerospace and flight-critical systems. A number of practical key factors for designing credible technological options are emphasized. Such considerations are decisive for the survivability of the design during ground/flight Validation & Verification (V&V) activities. The views reported in this paper are based on lessons learnt and results achieved through actions undertaken with Airbus during the last decade. As an illustrative example, a model-based fault monitoring technique is presented which has reached level 5 on Technological Readiness Level scale under V&V investigations at Airbus.

1. Introduction

Strongly affected by globalization, the aerospace industry is a powerful engine of innovation as it has to meet more and more aggressive performance targets in reliability, efficiency, safety, weight, range, environmental impact and emissions, etc. The challenges today are far greater than those faced in the past and continue to grow as individual systems evolve and operate with greater autonomy and intelligence within a networked and cyber–physical environment (Sampigethaya and Poovendran, 2013). Regulatory standards evolve as the industry matures, and evolutionary improvements to existing systems should be supplemented by revolutionary technologies and concepts to support conventional industrial practices. Innovative FDIR systems are required to achieve improved flight performance and efficiency. The primary objective of a FDIR system is (i) early detection of faults and abnormal events with low false alarm and missed detection rate, isolation of their location and diagnosis of their causes, and (ii) planning subsequent automatic reconfiguration actions in case of degraded flight conditions. Varying degrees of FDIR sophistication have been around for more than five decades for aerospace systems. For technical and development reasons, FDIR functions of a spacecraft are conventionally arranged in a hierarchical architecture in which several levels of faults are defined from local component/equipment/unit level up to global system failures. The higher the level, the more critical the fault but lower the occurrence probability of the fault. Fault recovery and system reconfiguration is achieved by switching to redundant units and backup mode using inactive hardware redundancy schemes. See for example (Wander and Förstner, 2012). On the other hand, FDIR issues have spurred on substantial research effort within the academic community and an impressive array of publications have been generated. Among others, see for example Gao et al. (2015); Hwang et al. (2010), Blanke et al. (2003), Ding (2008), Chen and Patton (1999), Patton and Frank (2000), Zolghadri (2000), Cieslak et al. (2010), Isermann (2005, 2006), Ducard (2009), Edwards et al. (2010), Zolghadri et al. (2014) and Fekish (2014). When exploring this rich literature, one may have the feeling that advanced FDIR designs and methods have already found many applications into aerospace arena. By application, it is understood “tangible and marketable aerospace technologies which can generate economic added value and benefits to society”. However, we have to recognize that in terms of applications the assessment is not overly enthusiastic and the current situation reveals a mixed picture. It is hoped that the views reported in this paper can be helpful to reflect about where the effort should be put to improve this situation in the future. For this, we need to understand how we got where we are today. The analysis is grounded in author’s experience in model-based FDIR

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Abbreviations: EFCS, Electrical Flight Control System; FBW, Fly-By-Wire; FCC, Flight Control Computer; GNC, Guidance, Navigation and Control; FDD, Fault Detection and Diagnosis; FDIR, Fault Detection, Identification and Recovery; FTC, Fault Tolerant Control; FTG, Fault Tolerant Guidance; GNC, Guidance, Navigation and Control; LOC-I, Loss Of Control In-flight; ADIRS, Air Data Inertial Reference System; V&V, Validation & Verification; TRL, Technology Readiness Level; SIB, System Integration Bench; SCADE™, Safety Critical Application Development Environment

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research,[1] and the conclusions reached embrace mainly the European situation, although beyond the old continent one can find certainly strong parallels and similarities with the situation in other places.

To begin with, it is thought that a brief history of modern control design can be helpful to better situate the emergence of fault tolerant control and fault diagnosis problems which have been widely motivated by flight-critical applications. The field of modern control may sometimes appear as a collection of disparate topics, tricks and modifications to the earlier works; one is often confused and overwhelmed by the vast number of what appear to be unconnected and separate designs and methods. So, to set the scene and before going through the FDIR era, the paper starts with a short background of linear control theory. This rapid overview is presented in the following section in the form of two acts and four scenes. Links with aerospace and flight systems are briefly traced. Section 3 is dedicated to industrial state of practice in aerospace. Section 4 is an attempt at explaining the widening gap between advanced methods being developed by the academic control community and technological solutions demanded by the aerospace industry. Section 5 provides an example and some concluding remarks and final thoughts are provided in Section 6.

2. Historical overview

2.1. Classical control theory

In the 1940s, the concept of linear control systems and feedback theory emerged with the work of Bode, Ziegler and Nichols using graphical techniques in the frequency-domain. The controllers that were built where PI and PID controllers, they were not model-based. The controllability was defined as the ability of the process to achieve and maintain the desired equilibrium value (Ziegler and Nichols, 1943). Robustness concepts were incorporated in the design techniques in the form of gain and phase margins. Frequency domain techniques and PID control are still the tool of choice in flight control analysis and design. For example, the longitudinal and lateral equations of motion can be approximated by a set of linear differential equations and the frequency tools help aerospace control engineers gain useful insight on how to improve robustness and performance of feedback loops.

2.2. Modern control theory

In the 1960s, and following the seminal work of Kalman (1960), linear stochastic control has emerged and Linear–Quadratic–Gaussian (LQG) control and model reference control became major new design techniques. The major impact of Kalman's work was the replacement of graphical design techniques by model-based certainty equivalence control design (Trentelman and Willems, 1993). However, the Achilles' heel of the model-based control era of the sixties and seventies was plant model uncertainties. LQG design had failed to address the "essential requirement that changes of loop gains in all combinations should leave the system with an adequate stability margin" (Rosenbrock and McMorran, 1971; Athans, 1971; Doyle, 1978; Horowitz and Shaked, 1975). During this period, the gap between academic theory and engineering practice in the control field increased. In the late 70s and early 80s, a renewed interest appeared in the problem of plant uncertainty. At about the same time, some significant results were being reported on the analysis of multivariable systems in the frequency domain and a multivariable robust design philosophy emerged, which was identified as the LQG/LTR (linear–quadratic–Gaussian/loop transfer recovery) approach. Robust multivariable feedback design methods flourished in the early 80s, where the main focus was the use of singular values in the design of robust multivariable systems in the frequency domain (Youla and Bongiorno, 1985; Zames, 1981; Safonov et al., 1981; Doyle and Stein; Maciejowski, 1989). A good retrospective analysis is provided in Safonov (2012). On the other hand, interest in adaptive control grew significantly from the mid-1950s (Aseltine et al., 1958; Bellman, 1961). A great number of ideas on adaptive control were proposed since then (Aström and Wittenmark, 1995): model reference adaptive system, the self-tuning regulator or dual control... The stability problem was an important challenge that led to interesting developments in stability theory. Barbalat's lemma constituted the corner stone of providing stability for adaptive systems (Aström and Wittenmark, 1995). Here, again, the role of simplified models and the robustness to neglected dynamics were major questions. In the above mentioned developments, flight control has been often a driving force. Supersonic flight posed new challenges for flight control and control systems for ballistic missiles emerged as an important topic in the post-Sputnik era (Aström, 1995). Several flight-tested systems based on model reference adaptive control are mentioned in Aström (1995).

2.3. Fault detection and diagnosis

In the early 1970s, Fault Detection and Identification (FDI) has emerged within the control community. Generally, the main desirable characteristics of a FDI system are early detection, good ability to discriminate between different failures, good robustness to various uncertainty sources, and high sensitivity and performance, i.e. high detection rate and low false alarm rate. In the early works, innovation signals were used to design detection filters. See for example Beard (1971), Jones (1973) and Mehra and Peschon (2012). Many solutions have appeared during the 1980s: parity space and observer-based approaches, eigenvalue assignment or parametric based methods. In the 1990s, a great number of publications dealt with specific aspects such as robustness and sensitivity, diagnosis oriented modeling or robust isolation. Among others, see for example Gao et al. (2015), Hwang et al. (2010), Patton and Frank (2000) and Zolghadri et al. (2014) for a survey. More recent design methods include, nonlinear local filtering and nonlinear observers, geometric and set membership methods, robust, LPV and multi-model designs, or sliding mode techniques. Today, model-based FDI design can be considered as a mature field of research within the control community. The evidence of this can be seen through the very significant number of publications and dedicated conferences. For flight vehicles, off-normal behaviors are complex, often resulting from an array of causal and contributing factors acting habitually in combination. The diverging effects of a fault may take shape gradually, interact with other factors within the subsystem, and its consequences spread slowly throughout the vehicle. Malfunctions may occur in sensors, actuators or other devices. For example, the aircraft state is measured by a set of sensors delivering e.g. anemometric and inertial measurements that characterize the aircraft attitude, speed and altitude. The data is acquired using an acquisition system composed by several dedicated redundant units. The measurements are processed to compute consolidated flight parameters to be used by FCC. Usual failures include oscillations, bias, drift, loss of accuracy, calibrations errors, freezing... Another example is malfunctions in control surface servo-loops (elevators, ailerons, rudders...). For instance, an oscillatory failure could excite the airplane structure producing undesirable structural loads (Goupil, 2011). In Osder (1999) one can find a comprehensive analysis on redundancy management in aircraft systems. See also Marzat et al. (2012) and the references therein for a comprehensive survey. A lot of aerospace case studies have been reported in the open literature, see for example many technical reports available at: http://www.sti.nasa.gov/.

[1] One of the model-based monitoring methods that the author developed with Airbus received certification on new generation A350 aircraft and is flying since January 2015 (Zolghadri et al., 2015).