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The challenge of advanced FDI algorithms for aircraft systems

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Abstract: What is the Achilles' heel of academic Fault Detection and Isolation (FDI) methods when it comes to application to real aircraft systems? This paper discusses some major and decisive issues that stand in the way of their transition from lab developments and simulations to real life applications in aeronautics. Often underestimated by academics, these issues determine the survivability of a new design for final V&V (Verification & Validation) activities. The paper recalls some practical items that should be considered at the design stage to help reach high Technological Readiness Level (TRL) scales for a given FDI algorithm. The paper will also take a look in the future and the way forward to anticipate future needs.

Keywords: Fault Detection and Isolation; Application to aircraft systems

1. INTRODUCTION

Today, the state-of-practice to detect faults and unexpected events in aircraft systems is mainly based on cross checks, consistency checks, voting mechanisms, and Built-In Test techniques. Recovery and system reconfiguration are achieved by a set of redundant equipment, typically by switching to a fault-free channel and ignoring the output of the failed channel. These techniques are the standard industrial practice and implemented in all modern airplanes, and fit into current certification processes. Advanced FDI techniques may be useful to support the current industrial state-of-practice by contributing to incremental and evolutionary improvements of existing systems. However, they encounter serious barriers when one attempts practical real-world applications in aeronautics. The objective of this paper is to underline some important issues which stand in the way of practical implementation of academic FDI methods. The analysis reported in this paper is grounded in authors' experience and lessons learned during various collaborative projects in Europe. It is hoped that the views reported in this paper could be useful to help shape FDI methods early at the design stage for successful implementation. The paper will also take a look in the future and the way forward to anticipate future needs. It is not obvious to predict where the things are going in aviation, but there is no doubt that future systems will operate with greater autonomy and intelligence. The authors believe that we have reached a turning point in FDI design: we are moving from the established FDI theory investigated to date, to trustworthy, cross-domain, evolvable and distributed FDI within a connected and distributed cyber-physical flight environment.

The paper is organized as follows. Section 2 provides a very short synopsis of academic FDI developments. Section 3 is dedicated to industrial state of practice in aeronautics. Section 4 recalls some practical design considerations and technological solutions demanded by the aircraft industry. Section 5 focuses on future challenge in civil aviation. Finally, some final thoughts are provided in Section 6 with ten key messages proposed as takeaways.

2. FDI: ACADEMIC STATE OF THE ART

This section is intended to provide a short synopsis rather than an exhaustive survey of FDI methods. In the early works, innovation signals were used to design detection filters. See for example (Beard 1971), (Jones 1973) and (Mehra and Peschon 1971). Many solutions have appeared during the 1980s: parity space and observer-based approaches, eigenvalue assignment or parametric based methods. See for example (Isermann 2006), (Chen and Patton 1999), (Zolghadri 2000). In the 1990s, a great number of publications dealt with specific aspects such as robustness and sensitivity, diagnosis-oriented modelling or robust isolation. See for example (Gao et al. 2015), (Hwang et al. 2010), (Ding 2013), (Isermann 2011), (Zolghadri et al. 2006). Among many others, applications to aircraft benchmarks and test facilities can be found in (Zolghadri 2000, 2016), (Berdjag et al. 2012), (Cieslak et al. 2010). Other design methods include nonlinear filtering and observers, geometric and set membership methods, LPV designs, or sliding mode techniques. For decision making, the simplest way is to use a constant threshold. For fault detection in flight systems, the thresholds are flight conditions-based thresholds validated with all the known delays and uncertainties in the signal propagation (acquisition, frequency, filtering…). Usual sensor failures include oscillations, bias, drift, loss of accuracy, calibrations errors, freezing. See for example (Goupil et al. 2015) where the problem of sensor fault detection in aircraft systems is discussed. Another example concerns malfunctions in aircraft control surface servo-loops (elevators, ailerons, rudders…).

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For instance, an oscillatory, a runaway or a lock-in-place failure of a control surface could excite the airplane structure producing additional structural loads, or impact the aircraft controllability if not detected early enough (Goupil 2011), (Zolghadri 2018a and 2018b), (Gheorghe 2013). It must be considered as early as possible in the aircraft development in order to optimize its structural design. Many case studies on FDI for aircraft systems have been reported in the open literature. A simple keyword search in Internet provides hundreds of examples. In (Osder 1999) one can find a comprehensive analysis on redundancy management in aircraft systems. In the past few years, some papers have appeared on distributed fault management, see for example (Zhang and Zhang 2012), (Reppa et al. 2015), (Teixeira et al. 2014), (Xu et al. 2020). On the other hand, a number of methods for safe flight envelope prediction have been reported. Many of them are formulated in terms of state reachability. The safe flight envelope is defined as the intersection of the forward and backward reach sets where all states can be reached and then controlled back to the initial state. See for example (Mitchel et al. 2005), (Oishi et al. 2008), (Lombaerts et al. 2015), (Schuet et al. 2014). Some other techniques can be found in (Van Oort et al. 2010), (Allen and Harry 2011), (Tang et al. 2009), (Pandita et al. 2009), (Tekles et al. 2016), (Lombaerts et al. 2016). A number of investigations deal with the problem of Loss of Control In flight (LOC-I) margin estimation. LOC-I includes significant, unintended departure of the aircraft from controlled flight, the normal flight envelope, or usual flight attitudes. LOC-I is often a multiple-hazards event leading to unpredictable aircraft behavior (Belcastro 2012). Among others, see for example (Krishnakumar et al. 2012), (Poolla and Ishihara 2015) and the references therein. Upset prevention and recovery has been addressed in several AIAA publications, see for example (Smaili et al. 2017), (Lombaerts et al. 2017), (Schuet et al. 2017), (Krishnakumar et al. 2014), (Stepanyan et al. 2016), and the references therein. It should also be noted that the adoption of Fly-By-Wire (FBW) systems on civil aircraft has brought many benefits including flight envelope protection functions as part of the Flight Control Laws. This additional protection helps prevent LOC-I events.

An obvious observation from the above short synopsis is that the literature is now overwhelmed by a huge number of various designs, techniques and methods related to fault detection, diagnosis, recovery and safety margin estimation. However, the fact remains that their application to real aircraft systems has remained very limited. By application, it is understood "transfer of knowledge resulting in tangible and marketable aerospace technologies which can create economic added value and benefits to society". In the rest of the paper, some helpful guidelines are provided to foster real world applications to aircraft systems. For this, the industrial state of practice is first briefly reviewed in the following section.

3. FDI: INDUSTRIAL STATE OF PRACTICE

The current state of practice applied by aeronautic practitioners makes use of two main approaches: signal processing techniques and trivial model-based approaches. On the one hand, the first data-driven family encompasses simple techniques like limit or threshold checking (e.g. checking if a sensor measurement lies between two nominal bounds or if its dynamics is bounded), comparisons between redundant information (cross-checks and consistency checks), voting schemes, filtering, comparison between system inputs and outputs… and many other built-in techniques of varying sophistication. This data-driven approach relies a lot on the system knowledge, also termed "Engineering Knowledge", and on the system architecture choices. On the other hand, some basic model-based approaches are already in-service, comparing a real sensor measurement with a very simple model like e.g. a simple transfer function representing the average behavior of the system to be monitored. It includes physical models with constant parameters, representing the average behavior expected in nominal conditions. The Engineering Knowledge is also key with this kind of approaches. In practice, a mix of both approaches is used in the sense that a signal processing technique is often used for the decision-making step on the residual of a model-based approach. Some identification techniques can be used as well to produce a black-box model in a model-based approach. Merging physics-based models and experimentally identified models is a good example of this combination of data-driven and model-based strategies.

In all cases, Engineering Knowledge is the cornerstone. In terms of fault identification, dedicated fault detection solutions are developed for each type of faults. This means that there is no need for such an identification as the fault type is de facto known.

4. PRACTICAL DESIGN CONSIDERATION

4.1 Complexity of the design

Academic solutions proposed to tackle practical problems can turn out to be very consuming in terms of operations as non-optimized for real-time frameworks. That is why before integrating such solutions in an industrial platform (e.g. implementing real-time embedded code in an avionics computer) the corresponding computational load must be assessed and if possible optimized to alleviate the corresponding burden (e.g. parameterization, dead code removal, code simplification…). Designs that require a huge number of on-line operations are discarded. Indeed, a Flight Control Computer is in charge of many functions (flight control law computation, servo loops, data exchanges between computers, input/output monitoring, etc…) and a single monitoring (e.g. a sensor or actuator FDI algorithm) cannot afford to consume more than 1 or 2% of the maximum CPU capacities, in the most comfortable case. A speaking example of the complexity management is the case where a complex and non-linear physical model must be embedded. If too complex, it can be replaced e.g. by a Look-up Table which can lead to some degradation of the model accuracy. A Neural Network model can also be a good alternative if it does not mean a higher complexity than the initial physical model. In all cases, the impact of the simplifications on the FDI design in terms of robustness and performance must be assessed. Moreover, the software development for critical systems is constrained by specific guidelines dealing with critical software used in certain airborne systems (cf. DO 178 - Software Considerations in Airborne Systems and Equipment

Certification), which guarantees the certification. In particular, it typically requires a stringent traceability from system requirements to all source code or executable object code. The design complexity does not have to significantly impact the traceability.

The current computer software specification practice relies mainly on a graphical language, very much in the Matlab/Simulink or SCADE style. It is a graphical representation linking together a limited number of symbols. The corresponding library typically includes basic elementary functions such as addition, division, switch, filters, rate limiter, flip-flop, logic gates, etc… It is very practical to code logical operations on binary inputs and as well to code basic processing. It also allows for coding almost any processing but depending of the complexity, the corresponding number of symbols can be huge and the readability becomes limited. Coding a conditional branch with a varying number of occurrences is tricky. Implementing high-order matrix computation remains difficult and non-deterministic computation like optimization routines is not possible. As a consequence, translating an initial design coded into a different environment (e.g. Python or Matlab) requires a significant effort that can in turn~~s~~ lead to certain limitations in terms of performance~~s~~.

4.2 Clear procedure for step-by-step tuning of the design

Academic researchers master the theoretical foundations of the designs that they have developed. However, there is generally a long way from a paper to an aircraft: additional efforts are required to reduce the complexity of the algorithms and especially their tuning. A procedure for an automatic tuning of the high-level design parameters is needed or at least to document the design with clear and detailed guidelines. Easy-to-tune and limited high-level parameters are decisive for the survivability of an advanced solution during Verification & Validation (V&V) activities. Indeed, on-board an aircraft there could be many different contexts of use and it is crucial to understand what needs to be adapted in relation to the system characteristics. An FDI design can be applied on different systems on-board the same aircraft (e.g. different control surfaces or actuators of different nature), for different aircraft with different features and missions (e.g. short-range or long-range aircraft). It has been observed that a simple and rudimentary well-mastered method may work better than a complex design that cannot be tuned properly by the end-user. A good example is an FDI design to monitor actuators. The most modern aircraft are typically fitted with conventional hydraulic actuators but also with more electric actuators like e.g. Electro-Hydrostatic Actuators (Van den Bossche 2006) and certainly in the future with fully electric actuators (Electro-Mechanical Actuators). The underlying physical principles are different and de facto the corresponding models to be used in an FDI design. An appealing avenue of investigation is to provide automatic tuning procedures via optimization approaches and with massive representative data.

4.3 Initialisations, robustness and sensitivity

The initialization of an algorithm is a key aspect for on-board implementation. Starting with default values of design parameters is quite trivial but the in-flight inputs can have various characteristics. In particular, as a reset of an avionics computer may occur during the flight, a fast convergence is required especially for fault having a sudden impact on the system. The reconfiguration of avionics systems is generally based on redundancy management, which means that a stand-by equipment or function must take-over after an abnormal behavior is detected and confirmed. It also means that potentially a stand-by equipment could also be in a fault-mode that is detected only when the hand-over is performed. It is termed a hidden or latent failure. To avoid such a situation, regular checks are performed but in case of a hidden failure occurring between two tests, this situation can be encountered. That is why it is important to detect a fault just after a reconfiguration and so to avoid a too long initialization phase. Another example concerns an FDI design relying on identified models which generally requires enough information in input to avoid poor convergence and to ensure consistent estimated parameters and outputs. If there is very poor information when the hand-over between an active and a passive system is performed, then an “initialization belt” is required.

In terms of robustness, on the one hand, on-board FDI generally deals with very rare events, so very low probabilities of occurrence. On the other hand, the Mean Time Between Failure (MTBF) of the avionics equipment, once converted in terms of probability, represents a more probable cause of losing the avionics equipment as it can be caused by plenty of failure causes. It means that the robustness of the FDI design must be compliant with these probabilities. In other words, there are more constraints on the False Alarm rate than on the Missed Detection rate, when referring to the safety assessment process and hazard analysis (failure conditions are categorized by their effects on the aircraft and their associated probability of occurrence).

In terms of sensitivity, as typically one FDI design is dedicated to one kind of fault, the influence of other types of fault must be carefully addressed in order to optimize the future maintenance task. For example, if an FDI design dedicated to oscillatory failures triggers in the presence of a control surface runaway, then the fault identification is required.

4.4 Verification and Validation activities

The Verification and Validation (V&V) activities are standard activities in industry, especially for complex products which can be considered as systems of systems. V&V process all along the V-cycle of an industrial product avoids discovering anomalies later on which means additional significant costs. The cost is growing exponentially between the earliest phases of the development and the entry into service of the product. According to the Industrial Referential ARP4754 (Aerospace Recommended Practice), the Validation is the “determination that the specification for a product is correct and complete to ensure that the final product meets the operational needs of the user”. In other terms, the question to answer is “are we building the right system?”. The Verification ensures that the “evaluation of an implementation of the specification meets a set of design specifications”. In other words, the question to answer is “did we correctly build the system?”. Dealing with FDI design, the definitions are the same and the “system” can be replaced by the word “design”. Referring to the title of this paper about the on-board implementation of advanced FDI algorithms for aircraft systems, and addressing academic activities, the Verification is of primary interest assuming that the Validation is rather on the industrial side (i.e. ensuring that the upstream specification is complete and correct, and already considered in the design). The Verification must be as complete as possible and must not only address average and standard flight conditions but must also address unusual and non-standard conditions, also informally termed "corner cases". In summary, all operating conditions must be covered. As an example, considering a simple model-based approach, using a simple fixed threshold could not be sufficient and a more adaptive threshold could allow to adapt to extreme situations. Considering a given FDI design with a given set of inputs (sensor measurements…), it is for example needed to verify the design by sweeping a wide range of noise level on the sensor measurements, but also to assess the consequences of other failure cases on some key inputs. This allows for determining the limitations of the design robustness and performance with respect to the varying input conditions, i.e. the envelop of nominal behaviour. But the key message behind this last example is that the FDI design should be independent and dissimilar from the function being monitored. For instance, if a control surface abnormal position is due to a single failure, e.g. a sensor failure, then this faulty sensor measurement does not have to disable the corresponding FDI design in charge of detecting the control surface abnormal position.

4.5 Determinism and certification requirements

Aircraft are designed to prescriptive safety and airworthiness codes and regulations. One of the golden rules is that new technologies are used in practice only when clear benefits can be demonstrated, like for instance performance improvement (e.g. fuel consumption), new function to support the pilots (e.g. Runway Overrun Prevention System – ROPS (Jacob et al. 2009)) or reduction of recurring (e.g. system equipment) and non-recurring (e.g. development) costs. It means that beyond the FDI design itself, its benefits within the function hosting the design must be demonstrated, at a higher level. These new technologies themselves do not have to introduce new risks and regressions compared to the state of practice. In terms of V&V, for any new technology the certification process possibly relies on a combination of several incremental steps in terms of representativeness and test mean fidelity: theoretical analysis; simulation and/or lab tests (e.g. failure simulation, sensitivity analysis, Monte-Carlo campaign…); ground/flight tests; replay of known and available real events; evaluation on massive flight data available from Airline operational flights. Another primary requirement for certification is that the systems operate deterministically. A model-based design is deterministic if given the initial state and the inputs, the design exhibits exactly the same behaviour, whatever the situation (environmental conditions, flying configuration…). It means that for a given set of inputs it will always produce the same outputs. Today, certification of non-deterministic systems is still not possible, and this is an issue for many academic designs available. Last but not least, determinism also eases the V&V activities and ensure good confidence in it. The verification of a non-deterministic design does certainly require specific methods and means that are not yet part of the industrial state of practice.

4.6 Modularity, capacity of adaptation and genericity

Aeronautics products are typically long life-cycle products. A flying machine, and especially a civil aircraft, experiences numerous software and hardware generations which means challenges related to lifecycles, especially to deal with equipment obsolescence. As an example, on a civil aircraft the software cycle ranges from 6 to 12 months, the hardware cycle oscillates between 3 to 5 years, the aircraft itself upgrade can occur between 6 to 15 years and the aircraft production can last between 30 to 50 years. This means significant challenges to improve existing algorithms or to bring new algorithms coping with current and old architectures.

In this context, innovative FDI solutions must fit in the existing mature and proven state of practice. That is why an incremental development is often suitable, which could mean e.g. adding a new module or adapting an already existing unit in the current solutions. It is crucial for the academic researchers to understand correctly the industrial state of practice and to spot where some modules can be adapted or modified without changing the complete and already certified initial design.

In this context, the design genericity is of primary interest: in order to optimize non-recurring development costs, to optimize the production rate and to minimize the development time, reusable and generic technics are suitable. The collateral benefits also include e.g. the application of the same tuning procedure and same Verification and Validation activities.

5. ANTICIPATING FUTURE NEEDS

Thanks to new innovative and disruptive technologies, in the recent digital transformation context, the aircraft industry is under complete transformation. In civil aviation operations, the next leap forward could be to take one pilot out of the cockpit (single pilot operations, SPO). See for example (Bailey et al. 2017). In SPO, the root problem is that the coordinated crew will not be available as a resource. SPO will require on-board and ground-level specific flight services. What cannot be negotiated by the plane makers is that the safety should remain unchanged, or even improved. So, the combination of these two challenges (autonomy and safety) requires trustworthy, robust and scalable detection and mitigation of anomalous events. For the foreseeable future and given the predicted demands on aviation, smart model-based FDI technologies will still have some beautiful days ahead. They are required to help enable paradigm shifts in future flight operational issues management, and should act as a bridge between today's operations and tomorrow's demands. 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. This will create numerous new opportunities and exciting challenges in which the FDI academic community could play an important role. In particular, the aforementioned context means that more automatism will be embedded, with more complexity, higher level functions and more interactions between systems. A multidisciplinary approach seems unavoidable. As an example, some system failures can impact the structural design optimization of the aircraft (Goupil, 2010) and this will be even more the case in the future for aircraft with more efficient wings (e.g. more flexible and with flutter control). A second example concerns fault-tolerant multi-sensor data-fusion for flight navigation during approach and landing in the SPO context. The challenge is to integrate several heterogeneous information sources to ensure the system availability and to assist the single pilot for correct management of the final flight phase (Ifqir et al. 2021). The sensors of interest are typically Inertial Reference System, Global Positioning System and Instrument Landing System. As a last example, it is worth stressing the link between FDI and maintenance: the FDI designs feed the maintenance information and serve to define the relevant maintenance tasks. The current state of practice is rather to equip each avionics system with a dedicated built-in test equipment (BITE) in charge of sending FDI information to a centralized maintenance system. In the future, due to the growing complexity of systems and to the presence of more complex and transverse functions, the trend could be to remove the unitary BITEs and to directly feed a centralized powerful algorithm in charge of synthesizing the maintenance information thanks to a global view of the aircraft state.

6. FINAL WORDS

There exists today a widening gap between advanced academic methods and real-world aircraft applications. In this paper some of major causes for this situation have been discussed. The paper also underlined some directions to anticipate future needs in civil aviation operations. Our key “takeaways” are the “messages” discussed all along this paper. We reiterate these in the Table below. It is notable that the messages all reinforce the need for a closer and more open collaboration between Academia and Industry.

Table 1: 10 key messages for the FDI research community

1- The current Industry state of practice relies on mature and proven basic technological solutions which bring added-values on the final product
2- There is now a need to apply disruptive solutions to achieve the next leap forward, especially towards more Autonomy
3- The FDI research community is broadly unaware of the industrial requirements
4- The academic solutions, if too complex, must be optimized to alleviate the corresponding burden, and the impact in terms of robustness and performance must be assessed.
5- A clear procedure for step-by-step tuning of the design is required due to the wide range of application contexts and to support the implementation by non-specialists
6- Initializations, robustness and sensitivity are key for compliance with operational constraints and reconfiguration management.
7- Verification is key for on-board advanced FDI designs and must covered all operating conditions.
8- Determinism is key for certification
9- New technologies are used in practice only when clear benefits can be demonstrated
10- Incremental development is often suitable

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