

Analytical redundancy-based FDI techniques for real-world aerospace systems: where are we today?

A. Zolghadri

Abstract—Advanced model-based FDI (Fault Detection, Identification) challenges range from pre-design and design stages for upcoming and new programs, up to the improvement of the performance of in-service flying systems. However, today, their application to real aerospace world has remained extremely limited. The paper underlines the reasons for a widening gap between the advanced FDI methods being developed by the academic community and technological solutions demanded by the aerospace industry.

Nomenclature

EFCS = Electrical Flight Control System
FBW = Fly-By-Wire
FCC = Flight Control Computer
FDI = Fault Detection and Identification
FDIR = Fault Detection, Identification and Recovery
FTC = Fault Tolerant Control
FTG = Fault Tolerant Guidance
GNC = Guidance, Navigation and Control
HMI = Human Machine Interface
LTI = Linear Time Invariant
LPV = Linear Parameter Varying
TRL = Technology Readiness Level

I. INTRODUCTION

Recent developments in control engineering have attractive potential for resolving numerous issues related to improved Guidance, Navigation & Control (GNC) of the flying systems, including improved flight performance, self-protection and extended life of structures. Innovative and viable fault detection & diagnosis and fault tolerant control and guidance technologies that will improve spacecraft safe operation and availability pose significant new challenges, ranging from pre-design and design stages for upcoming and new programs, to the performance improvement for flying in-service systems.

The goal of a FDI unit is to detect, isolate and estimate the severity of a fault. A fault can be defined as an unpermitted deviation of at least one characteristic property or parameter of the system from the standard condition [7]. Such malfunctions may occur in the individual unit of the plants, sensors, actuators or other devices and affect adversely the local or global behavior of the system. Generally, the main desirable characteristics of a FDI system are [1], [2]:

- Early detection and diagnosis of abnormal situations, i.e. detection delay should be minimized.

- Good ability to discriminate between different failures (isolability).
- Good robustness to various noise and uncertainties sources, and their propagation through the system.
- High sensitivity and performance, i.e. high detection rate and low false alarm rate.

Once faults are correctly diagnosed, the reconfiguration unit utilizes information on the estimated fault and adjusts the controller parameters to recover the system from the faulty conditions [3], [14], [15], [63], [65], [66], [68], [75]. Note that the recovery and reconfiguration actions can have different goals and characteristics depending on the considered system. FTC (Fault Tolerant Control) systems seek to provide, at worst, a degraded level of performance in the faulty situations. For aerospace vehicles, FTG (Fault Tolerant Guidance) could provide a greater flexibility for safe recovery when the available on-board control resources would not be sufficient [14]. This means on board reshaping of the mission objectives. Fault tolerant control and guidance provide means by which a potentially dangerous behavior of the system is suppressed if possible, or means by which the consequences of a dangerous behavior are avoided. FTC and FTG are integrated at the GNC level of the flying system.

So far, the advanced methods being developed by the academic research community have not been really accepted by the aerospace end-users. The reason is mainly related to the fact that a number of important aspects are often underestimated (or missing) in the classical academic publications: tuning, complexity of the design, real time capability, modularity and possibility to “reuse” or “build around it”, evaluation of worst-case performance, robustness in harsh environment, etc. Unfortunately, the lack of consideration of these characteristics has led to a widening gap between the advanced scientific methods and technological solutions demanded by the aerospace industry and end-users. The scope of this paper is to provide an analysis for this situation.

The paper is organized as follows. Section 2 presents a brief overview of the industrial state-of-practice. Section 3 is devoted to the brief review of the available academic literature. Section 4 highlights the slow-developing progress of the advanced academic methods to real-world aerospace systems. Finally, section 5 discusses some future challenges and opportunities.

A. Zolghadri is with the University of Bordeaux, CNRS-IMS lab, 351 cours de la Libération, 33405 Talence Cedex, France. phone: 33-5-40002416; e-mail: ali.zolghadri@ims-bordeaux.fr.

II. BRIEF REVIEW OF THE INDUSTRIAL STATE-OF-PRACTICE

A. General ideas

The basic issues involving general health management architecture tradeoffs changed little from the 1960s, although the hardware mechanizations of the earlier analog systems have been replaced largely with the software of the newer digital systems [40]. The conventional techniques currently in use in aerospace systems are now industrially well mastered and well characterized, and all expected failures are anticipated and uncovered. The hardware redundancy-based technique is the standard industrial practice and provides high level of robustness and good performance. Fault detection is mainly performed by cross checks, consistency checks, voting mechanisms, and built-in test techniques of varying sophistication. For instance, a typical commercial aircraft's navigation sensing system can contain triple-redundant inertial references plus triple-redundant air data sensors. A voting scheme monitors and checks the performance of the individual sensors and detects abnormal behavior. Flight conditions-based thresholds, once validated with all the known delays and uncertainties in the signal propagation (acquisition, frequency, filtering . . .), are used for rapid recognition of out-of-tolerance conditions. In setting these thresholds, compromises have to be made between the detection size of abnormal deviations and false alarms because of normal fluctuations of the variables. Fault tolerance relies mainly on hardware redundancy, safety analysis, dissimilarity, physical installation segregation and hardware/software reconfiguration [39]. Today, these standard FDI techniques are implemented in all aerospace systems and also correspond to current certification processes. The main advantage of their simplicity is that it allows designers and operators to use and manage them easily.

B. Avionics

The paper [38] focuses on a typical Airbus EFCS (*Electrical Flight Control System*) and provides a detailed description on the industrial practices and strategies for FDI in civil aircraft. The EFCS constitutes an industrial standard for commercial applications. Note that, the EFCS development on modern civil aircraft led also to a growing complexity of systems and equipment. Consequently, the number of failure cases to consider in the aircraft design has increased compared to the historical mechanical flight control system. In particular, system design objectives originating from structural load constraints are more and more stringent for satisfying the newer societal imperatives towards future "sustainable" aircraft (quieter, cleaner, smarter and more affordable). It can be demonstrated that improving the performances of fault diagnosis in EFCS allows designers to optimize the aircraft structural design (weight saving) and then to improve the aircraft performance and to decrease its environmental footprint (less fuel consumption and noise). The state-of-practice, applied worldwide by all aircraft manufacturers, to diagnose these EFCS faults and obtain full flight envelope protection at all times is to provide high levels of hardware redundancy in order to perform consistency tests and cross checks. This also ensures sufficient available control action (fault tolerance). For

example, a runaway is an uncontrolled control surface deflection that can go until moving surface stops if it remains undetected [14], [44], [74]. This failure situation creates additional loads on the aircraft structure and could also disturb the aircraft control. Runaways are mainly due to electronic component failure, mechanical breakage or FCC (*Flight Control Computer*) malfunctions. The industrial state of practice to detect control surface runaway is generally to compare the actual surface position to the theoretical surface position computed by the monitoring channel. An error signal is generated and the decision making corresponds to a threshold-based approach: if the signal resulting from the comparison is greater than a given threshold during a given time window, then fault detection is confirmed. A detected runaway will result in the servo-control deactivation or computer passivation. Note that a smaller deflection means less loads generated on the aircraft structure, that is why a fast and robust FDI is needed.

C. Space missions

For space missions, health monitoring is managed through a FDIR hierarchical approach in which several levels of faults are defined from local component/equipment up to global system failures. FDIR strategy can be divided between all levels: detection and local reconfiguration in the subsystems, fault diagnosis and global reconfiguration at the operational level, prevention at the decisional level (detect in advance PLANS THAT cease to be consistent with the actual resource usage and may lead to further failures ...). Depending on the mission needs, FDI functions are combined to other functions (data processing, orbitography, event-based commanding, and dynamic reprogramming) to achieve a desired level of availability, safety and autonomy [16], [23], [28], [43], [44], [61], [71], [72], [79]. The validation assumes testing all possible cross-path situations which becomes costly as the complexity of in-board hardware and software architectures increase. For early spacecraft, the above tasks were executed by sequential automata performing a priori known tasks. The usual implementation constraints found in aeronautics, such as computation load and complexity, are also encountered albeit to a greater degree due to the more limited weight and computational processing capabilities. Today, a satellite is a smart embedded system that is able to react to some know events and to select a decision among a predefined set. FDI is strongly related to autonomy needs that vary with the mission scenarios and the expected benefits. A low earth orbit satellite can be endowed with an autonomous orbit control function to reduce ground operations. A deep space spacecraft, due to long communication delays, will require FDI and automatic reconfiguration capacities. For other space systems such as winged atmospheric re-entry vehicles (space shuttle...) which have aircraft-like configurations and more redundant control actuation, there are also more limited weight capabilities compounded because of more restrictive aerodynamic and controllability characteristics resulting from their lower Lift-to-Drag ratios.

III. BRIEF REVIEW OF THE ADVANCED ACADEMIC RESULTS

A large body of literature on model-based FDI is now available. The "web of Science" reports around 4000 published papers on FDI topic during the last decade in all engineering fields. The theory related to FDI has been developed since the early 1970s, and can be considered today as a mature and well-structured field of research within the control community and offering many attractive features. FDI methods are classified generally into three categories, which include the knowledge or history based methods ([5], [59], [60]), analytical model based methods and signal based methods [9]. In this paper, we focus on analytical model based approaches. The early studies on model-based FDI appeared about forty years ago. In [24], [45] [46] and [47] innovation signals are used to design detection filters. Many basic solutions have appeared during the eighties: parity space and observer-based approaches, eigenvalue assignment or parametric based methods ([7], [10], [11], [12], [51], [56], [64]). In the nineties, a great number of publications dealt with specific aspects such as robustness and sensitivity, diagnosis oriented modeling or robust isolation [1], [9], [12], [15], [16], [46], [48], [50]. The European school has been very active in the development of this field, see for example and among others [1], [11]-[13], [56]-[61], [30], [54]. Today, and at least from a design point of view, model-based FDI 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 international conferences. The basic idea of model-based FDI is very simple and straightforward. See Fig. 1:

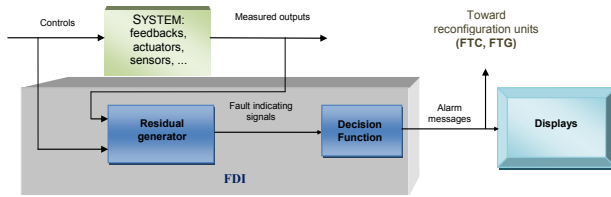


Fig. 1. Basic FDI structure

Residuals (fault indicating signals) are generated by the comparison of the system measurements with their estimates. A threshold function (fixed or variable) can be used to provide additional levels of detection, while for fault isolation the generated residual has to include enough information to determine that a specific fault has occurred. The core element is the residual generation. Note that if only fault detection is of interest, reconstructing the fault rather than detecting its presence through a residual signal can be a nice alternative solution, for instance by using a sliding modes observer ([15], [55]). Residual evaluation and decision making consist of checking the residuals and triggering alarm messages if the tolerances are exceeded. The thresholds can be set into different kinds. The simplest way is to use a constant threshold. The big advantage with fixed thresholds is their simplicity and reliability. Adaptive thresholds could enhance the sensitivity of fault detection with the optimal choice of the magnitude which depends upon the nature of the system uncertainties and varies with the system input. Adaptive thresholds can keep the false alarm rate small with an acceptable sensitivity to faults. In some applications, stochastic system models are considered and the residuals

generated are known or assumed to be described by some probability distributions. It is then possible to design decision tests based on adaptive thresholds. More robust decision logics use the history and trend of the residuals, and utilize powerful or optimal statistical test techniques. The well-known examples of these statistical test techniques are sequential probability ratio test (SPRT), cumulative sum (CUSUM) algorithm, generalized likelihood ratio test and local approach. See for example [9]. To enhance the robustness of FDI schemes against small parameter variations and other disturbances during residual generation, different design and evaluation tools have been proposed ([1], [2], [31], [49], [51], [53], [54]). The objective of any robust FDI method is to make the residuals become sensitive to one or more faults whilst at the same time making the residuals insensitive to modeling errors and uncertain disturbance effects acting upon the system being monitored. Robust FDI can be achieved if the residual signals maintain these sensitivity properties over a suitable range of the system's dynamic operation. A huge literature is now available dealing with various aspects of a FDI problem, ranging from modelling problems (nominal system modelling, fault modelling, disturbance and uncertainty modelling ...) and FDI system design. The available design methods includes methods based on LTI [1], LPV ([31], [52], [57], [58], [69]) and nonlinear/hybrid estimators/observers [13], robust designs inspired by robust control designs [51], unknown input observers [49], sliding modes methods [15] ... For example the interested reader can refer to [1], [2] for recent surveys. Observer-based approaches have arisen as one of the most popular among design techniques. In the linear case, it has been shown that any linear fault detection filter can be transformed into an equivalent observer-based form, providing a unified framework for analysis and implementation. The things get much more complex in the nonlinear case, from a design but also an analysis point of view. For a good survey on nonlinear FDI methods, the interested reader can refer to [13] and the references therein. Typically, the observer design problem is solvable if the system model can be transformed into a canonical form that may be a hard assumption to satisfy in many applications. An appealing approach to deal with some nonlinear problems is based on the LPV transformation.

IV. APPLICATION TO AEROSPACE SYSTEMS

There exists a number of "case study" in the open literature which are fragmented across many journal and conference papers (see for example and among others [20]-[30], [32]-[35], [58], [61], [62], [67], [68], [73], [74], [76]). For space missions, one can mention the precursor NASA's New Millennium Program [80]: here, the so-called Deep Space One (DS1) remote-agent experiment was initiated to demonstrate onboard fault-protection capabilities, including failure diagnosis and recovery, onboard re-planning following otherwise unrecoverable failures, and system-level fault protection [89]. The FDI challenges for aircraft flight control systems are being investigated within the European project ADDSAFE [78]. Analytical redundancy has been used on A380 for the detection of a very specific failure case [38]. However, to the best of the author's knowledge,

implementation of modern FDI / FDIR techniques has been extremely limited on board flying in-service systems.

Coming back to the industrial point of view, it is obvious that any modification to the existing in-service systems should be motivated, first of all, by a real industrial need. The choice of any "advanced" candidate solution should be clearly demonstrated in terms of added value from an industrial point of view. This means that any changes to the existing scheme should provide a viable technological solution ensuring either better performance while guaranteeing the same level of robustness, or better robustness for the same level of performance, or better performance and better robustness and covering larger fault profile. For proper implementation, those techniques should be embedded within the physical redundancy structure of the system.

Aerospace industry needs continuous improvement including insertion of new technologies that should be assessed by TRL (Technology Readiness Level) measure [78]. TRL provides a significant input to risk assessment of including a technology in an existing or new program. Roughly speaking, academic activities cover TRL1 (basic principles) up to TRL3 (laboratory and case studies, validation on high fidelity simulators ...). TRL6 (prototype demonstration)-TRL9 ("flight proven" through successful mission operations) correspond to technology integration and are well mastered by aerospace industry actors and end-users. However, a "dead valley" does exist which corresponds to TRL4-TRL5 (validation in relevant environment). This applicability gap has resulted in a real technological barrier.

Many of the early published academic papers on model based FDI start with the statements such as "hardware redundancy is expensive, heavy, less potentially reliable, it should be replaced by model based techniques whereby additional knowledge of the system is leveraged instead of actual redundancy ...". In light of the above observations, it appears that this basic and historical argument which played a driving role to motivate the early development of FDI academic research could be very misleading when applied to the aerospace vehicles. A good balance between conventional and in-service solutions and advanced model based techniques is probably the only right solution in many applications. This observation has been pointed out in [40] where the author developed several clever ideas about redundancy management.

V. FUTURE CHALLENGES AND OPPORTUNITIES

Advanced FDI techniques could have strong potentialities for widespread and real industrial applications in aerospace domain. Some facts allow us to be optimistic for the upcoming years:

- FDI methods and techniques are now well established and their conceptual and theoretical foundations are well mastered.

- FDI works in an "open loop" fashion with respect to the controlled system. So, FDI does not affect the stability and cannot bring the system into a dangerous configuration. Off

course this fact depends on how the FDI information is managed by the local or global R system.

- The innovative technological solutions used in modern spacecraft also introduce new sources of possible failures. The applicability of conventional techniques is becoming increasingly problematic when used in conjunction with the many innovative solutions being developed to increase performance. This feature motivates the use of more advanced FDI techniques. Moreover, increasing progress in on-board computational equipment and techniques has set the scene for the application of more sophisticated and powerful FDI methods.

- While clear-cut failures can be uncovered perfectly by the existing monitoring mechanisms, more subtle and soft drifting type failures must be detected and isolated by the use of more sophisticated FDI techniques.

- For aircraft applications, FDI can also be related to the situation awareness ([41], [42]). The aircraft internal situation perception, which can be called "situation assessment", relies on existing systems which monitor parameters, detect the error once it occurs, and inform the crew by HMI concept of "sudden alarm". With this concept, the system health is given by OK/NON OK information which can be not representative of the real status of the system. The early detection of a subsystem abnormality that is developing during flight would be potentially important, because the extra time before an alert range is reached may improve the crew's situation awareness. As situation awareness increases, the crew is increasingly able to think "ahead" of the aircraft, and do this for a wider variety of situations. Predictive FDI [34] could provide such possibility for rapid recognition of faulty situations which have the potential for early detection.

The academic literature on FDI is now saturated and the effort should be put toward the best suited FDI methods capable of handling the real-world aerospace FDI problems to overcome the "dead valley" as discussed in Section 3. An important issue is the need for clear, systematic and formalized guidelines for tuning, evaluation of worst-case performance and robustness in harsh environment. Also, a suitable candidate FDI method for any aerospace application should be able to manage stringent operational conditions in terms of trade-offs for FDI specifications, computational burden (memory storage, CPU load) and design complexity. The design method should provide high-level design parameters that can be used by non-expert operators. It should allow for easy integration of various kinds of specifications. It must also offer the possibility to reuse or to build around it, with adequate design and tuning engineering tools.

VI. CONCLUSIONS

Although the development of advanced model-based FDI techniques can be considered today as a mature field of research within the academic control community, their application to real aerospace world has remained very limited. In this work the focus was to show that while research on model-based FDI went forward since early seventies, the design methodology involving feasibility analysis and real world requirements specification is still

missing. A representative problem area remains the lack of effective procedures for maturing on-board implementation, validation and verification. In this paper, an attempt has been made to analyze major reasons for the slow-progress in applying advanced FDI methods to real-world aerospace systems and to discuss some future challenges and opportunities.

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VII. REFERENCES

- [1] Ding, S.X., Model-based Fault Diagnosis Techniques. Design Schemes, Algorithms, and Tools. Springer, Heidelberg, Berlin, 2008.
- [2] Hwang, S. Kim, Y. Kim, A survey on Fault Detection, Isolation and Reconfiguration methods, IEEE Transactions on Control Systems Technology, Vol. 18, N° 3, May 2010.
- [3] Blanke, M., Kinnaert M., Lunze M. et Staroswiecki M., Diagnosis and fault tolerant control. Ed. Springer, New York, 2003.
- [4] Venkatasubramanian, V., R. Rengaswamy, K. Yin, and S. N. Kavuri, A review of process fault detection and diagnosis part I: Quantitative model-based methods. *Comput. Chem. Eng.*, vol. 27, pp. 293–311, 2003.
- [5] Venkatasubramanian, V., R. Rengaswamy, K. Yin, and S. N. Kavuri, A review of process fault detection and diagnosis part II: Qualitative models and search strategies. *Comput. Chem. Eng.*, vol. 27, pp. 313–326, 2003.
- [6] Venkatasubramanian, V., R. Rengaswamy, K. Yin, and S. N. Kavuri, A review of process fault detection and diagnosis part III: Process history based methods. *Comput. Chem. Eng.*, vol. 27, pp. 327–346, 2003.
- [7] Isermann, R. Trends in the application of model-based fault detection and diagnosis of technical processes. *Control Eng. Practice*, vol. 5, no. 5, pp. 709–719, 1997.
- [8] Isermann, R. Model-based fault-detection and diagnosis status and applications. *Annu. Rev. Control*, vol. 29, no. 1, pp. 71–85, 2005.
- [9] Basseville, M., I. V. Nikiforov, Detection of Abrupt Changes: Theory and Application. Englewood Cliffs, NJ: Prentice Hall, 1993.
- [10] Patton, R., P. M. Frank, and R. N. Clark, Fault Diagnosis in Dynamic Systems: Theory and Application. Eds. Englewood Cliffs, NJ: Prentice-Hall, 1989.
- [11] Patton, R., Fault-tolerant control: the 1997 situation. SAFEPROCESS'97, Kingston Upon Hull, UK, 1997.
- [12] Chen, J. and Patton, R. J., Robust model-based fault diagnosis for dynamic systems. *Kluwer Academic Publishers. Boston/Dordrecht/London*.1999.
- [13] Bokor, J. and Szabo, Z. Fault detection and isolation in nonlinear systems. In *Annual Reviews in Control*, 33, 113-123, 2009.
- [14] Zolghadri, A., Advanced model-based FDIR techniques for aerospace systems: today challenges and opportunities, *Progress in Aerospace Sciences, to appear (available on line)* 2012.
- [15] Edwards, C. H. Alwi, Chee Pin Tan, Sliding mode methods for fault detection and fault tolerant control. In *Proceedings of the IEEE Conference on Control and fault-tolerant systems, SysTol'10*, Nice, France, 6–8 October Nice, France, October 2012.
- [16] Olive, X. FDI(R) for satellite at Thales Alenia Space: how to deal with high availability and robustness in Space domain? In *Proceedings of the IEEE Conference on Control and fault-tolerant systems, SysTol'10*, Nice, France, 6–8 October 2010.
- [17] Marzat J., Piet-Lahanier H., Damongeot F., Walter E. Model-based fault diagnosis for aerospace systems: a survey, *Proceedings of the IMechE, Part G: Journal of Aerospace Engineering*, 2012.
- [18] Schaefer, R. Unmanned aerial vehicle reliability study, *Office of the Secretary of Defense, Washington, DC*, 2003.
- [19] Henry, D., Zolghadri, A., Robust fault diagnosis in uncertain linear parameter-varying Systems. *IEEE International Conference on Systems, Man and Cybernetics 6*, pp. 5165-517. 2004.
- [20] Alcorta-Garcia E., Zolghadri A., Goupil P.. A Nonlinear Observer-Based Strategy for Aircraft Oscillatory Failure Detection: A380 Case Study. *IEEE Trans. Aerospace and Electronic Systems*. 2011 to appear.
- [21] Zolghadri A., Goetz C., Bergeon B., Denoise X. Integrity monitoring of flight parameters using analytical redundancy. *Proc. UKACC international conference on control (CONTROL '98)*, UK, pp. 1534–1539, 1998.
- [22] Zolghadri, A. An algorithm for real-time failure detection in Kalman filters. *IEEE Transactions on Automatic Control*, Vol. 41, N° 10, p. 1537-1540, 1996.
- [23] Kurtoglu, T.; Johnson, S.B.; Barszcz, E.; Johnson, J.R.; Robinson, P.I. 2008. Integrating system health management into the early design of aerospace systems using Functional Fault Analysis. *IEEE conf on Prognostics and Health Management* 2008.
- [24] Deckert, J.C., M. N. Desai, J. J. Deyst, and A. S. Willsky, “F-8 DFBW sensor failure identification using analytic redundancy,” *IEEE Trans. Autom. Control*, vol. 22, no. 5, pp. 795–809, Oct. 1977.
- [25] Wilbers, D.M., J. L. Speyer, Detection filters for aircraft sensor and actuator faults. *Proc. IEEE Int. Conf. Control Appl.*, Jerusalem, Israel, 2002.
- [26] Menke, T.E., P. S. Maybeck, Sensor/actuator failure detection in the VISTA F-16 by multiple model adaptive estimation. *IEEE Trans. Aerosp. Electron. Syst.*, vol. 31, no. 4, pp. 1218–1229, Oct. 1995.
- [27] Kim, S., J. Choi, and Y. Kim, “Fault detection and diagnosis of aircraft actuators using fuzzy-tuning IMM filter,” *IEEE Trans. Aerosp. Electron. Syst.*, vol. 44, no. 3, pp. 940–952, 2008.
- [28] Chen, R.H., H. K. Ng, J. L. Speyer, L. S. Guntur, and R. Carpenter. Health monitoring of a satellite system. *Proc. AIAA Guid., Nav., Control Conf.*, Aug. 2004.
- [29] Patton, R., Uppal F., Simani S., Polle B., Robust applied to thruster faults of a satellite system. *Control Engineering Practice*, vol. 18, n°9, pp. 1093-1109, 2010.
- [30] Falcoz A., Henry D., Zolghadri A. Robust fault diagnosis for Atmospheric Re-entry Vehicles: a case study. *IEEE Transactions on Systems, Man, and Cybernetics. Part A, Systems & Humans*, vol 40 , pp. 886-899, 2010.
- [31] Henry D., Falcoz A., Zolghadri A., Structured H ∞ /H- LPV filters for fault diagnosis: Some new results. *7th IFAC SAFEPROCESS*, Barcelona, Spain, 2009.
- [32] Henry, D., Fault diagnosis of the Microscope satellite actuators using Hinf/H- filters. *AIAA Journal of Guidance, Control, and Dynamics*. vol.31, no.3, pp.699-711, 2008.
- [33] Zolghadri, A. A redundancy-based strategy for safety management in a modern civil aircraft. *Control Engineering Practice*, Vol. 8, N° 5, pp 545-554, 2000.
- [34] Zolghadri, A. Early warning and prediction of flight parameter abnormalities for improved system safety assessment. *Reliability Engineering and System Safety*. vol. 16, pages 19-27, 2002.
- [35] Zolghadri A., Castang F., Henry D. Design of robust fault detection filters for multivariable feedback systems. *International Journal of Modeling and Simulation*. vol. 26 - pages 17-26, 2006.
- [36] Favre, C., “Fly-by-wire for commercial aircraft: The Airbus experience,” *Int. J. Control*, vol. 59, no. 1, pp. 139–157, 1994.
- [37] Briere, D., P. Traverse, Airbus A320/A330/A340 electrical flight controls—A family of fault-tolerant systems. *Proc. 23rd Int. Symp. Fault-Tolerant Comput.*, pp. 616–623, 1993.
- [38] Goupil, P., Oscillatory failure case detection in the A380 electrical flight control system by analytical redundancy. *Control Engineering Practice*, vol 18, issue 9, 2010.
- [39] Goupil, P., AIRBUS state of the art and practices on and FTC in flight control system. *Control Engineering Practice*, vol 19, pages 524-539, 2011.
- [40] Osder, S., Practical view of redundancy management, application and theory. *Journal of Guidance, Control and Dynamics*, vol 22, N° 1, 1999.
- [41] Palmer, M.T., K.H. Abbot. Effects of expected-value information and display format on recognition of aircraft subsystem abnormalities. *NASA Technical paper 3395*, 1994.

- [42] Regal, D.M., V.H. Rogers, G.P. Boucek. Situational awareness in the commercial flight deck - definition, measurement, and enhancement. *Proceedings of the 7th Aerospace Behavioral Technology Conference and Exposition, SAE*, pp. 65-69, 1989.
- [43] Johnson, D.M. A review of fault management techniques used in safety-critical avionics systems. *Prog. Aerospace Sci.*, Vol. 332, pp. 415-431, 1996.
- [44] Lemai S., X. Olive, M.C. Chermeau. Decisional architecture for autonomous space systems. *9th ESA workshop on advanced technologies for robotics and automation, Noordwijk, the Netherlands, November 28-30, 2006*.
- [45] Beard, R.V., Failure accommodation in linear systems through self-reorganization. Ph.D. dissertation, Dept. Aeronautics Astronautics, Massachusetts Inst. Technol., Cambridge, Feb. 1971.
- [46] Jones, H. L., Failure detection in linear systems. Ph.D. dissertation, Dept. Aeronautics Astronautics, Massachusetts Inst. Technol., Cambridge, MA, Feb. 1973.
- [47] Mehra, R.K., J. Peschon, An innovations approach to fault detection and diagnosis in dynamic systems. *Automatica*, vol. 7, pp. 637-640, 1971.
- [48] Massoumnia, M.A., A geometric approach to the synthesis of failure detection filters. *IEEE Trans. Autom. Control*, vol. 31, no. 9, pp. 839-846, Sep. 1986.
- [49] Chen J., R. J. Patton, and H. Y. Zhang, Design of unknown input observers and robust fault-detection filters. *Int. J. Control*, vol. 63, no. 1, pp. 85-105, 1996.
- [50] Chow, E.Y., A. S. Willsky, Analytical redundancy and the design of robust failure detection systems. *IEEE Trans. Autom. Control*, vol. 29, no. 7, pp. 603-614, Jul. 1984.
- [51] Stoustrup, J., and Niemann, Fault estimation—A standard problem. *Int. J. Robust Nonlinear Control*, vol. 12, pp. 649-673, 2002.
- [52] Bokor J., Balas G. Detection Filter Design for LPV Systems – a Geometric Approach. *Automatica*, 40, pp. 511-518, 2004
- [53] Raissi T., Videau G., Zolghadri A. Interval observers design for consistency checks of nonlinear continuous-time systems. *Automatica*, vol. 46, pages 518-527, 2010.
- [54] Efimov D., Zolghadri A., Raissi T. Actuators Fault Detection and Compensation under Feedback Control. *Automatica*, 2011
- [55] Yan X.G., Edwards C. Nonlinear robust fault reconstruction and estimation using a sliding mode observer. *Automatica*, 43, pp. 1605-1614, 2007.
- [56] Henry, D. and Zolghadri, A., Design of Fault Diagnosis Filters: A Multi-Objective Approach. *Journal of Franklin Institute*. Vol.342, No.-4, pp.421-446, 2005.
- [57] Zolghadri A., Henry D., Grenaille S. Fault diagnosis for LPV systems. *16th IEEE Mediterranean Conference on Control and Automation*, 2008.
- [58] Ganguli, S., Marcos, A., Balas, G., Reconfigurable LPV control design for Boeing 747-100/200 longitudinal axis. *American Control Conference*, 2002.
- [59] Cordier, M.O., P. Dague, F. Lévy, J. Mountmain, M. Staroswiecki, and L. Travé-Massuyès. Conflicts versus analytical redundancy relations: A comparative analysis of the model based diagnosis approach from the artificial intelligence and automatic control perspectives. *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 34, no. 5, pp. 2163-2177, Oct. 2004.
- [60] Travé-Massuyès, L., T. Escobet, and X. Olive. Diagnosability analysis based on component-supported analytical redundancy relations. *IEEE Trans. Syst., Man, Cybern. A, Syst. Humans*, vol. 36, no. 6, pp. 1146-1160, 2006.
- [61] Chen, R.H., H. K. Ng, J. L. Speyer, L. S. Guntur, and R. Carpenter, "Health monitoring of a satellite system," in *Proc. AIAA Guid., Nav., Control Conf.*, Aug. 2004.
- [62] Ganguli, G. Papageorgiou, and S. Glavaski. Aircraft fault detection, isolation and reconfiguration in the presence of measurement errors. presented at the *AIAA Guid., Nav., Control Conf., Keystone*, CO, Aug. 2006.
- [63] Edwards, C. *et al.* Fault Tolerant Flight Control – A Benchmark Challenge. *Lecture Notes in Control and Information Sciences*. 2010.
- [64] Henry D., A. Zolghadri, M. Monsion, S. Ygorra, Off-line robust fault diagnosis using the generalized structured singular values. *Automatica*, August, 2002.
- [65] Ding S.X., Integrated design of feedback controllers and fault detectors, *Annual Reviews in Control*, vol 33, 124-135, 2009.
- [66] Papageorgiou, C. and K. Glover. "Robustness analysis of nonlinear flight controllers". *AIAA Journal of Guidance, Control and Dynamics* 28(4), 639-648, 2005.
- [67] Marcos A. & Balas G., A robust integrated controller/diagnosis aircraft application. *Int. J. Robust NL Control*, 15:531-551, 2005.
- [68] Oudghiri M., Chadli M. & El Hajjaji A., Robust observer-based fault tolerant control for vehicle lateral dynamics, *Int. Journal of vehicle Design*, vol. 48, pp. 173-189, 2008.
- [69] Weng Z., Patton R. & Cui P., Integrated Design of Robust Controller and Fault Estimator for Linear Parameter Varying Systems, *17th World Congress IFAC*, Seoul Korea, 2008.
- [70] James M. and L. Dubon, "An autonomous diagnostic and prognostic monitoring system for NASA's deep space network," in *IEEE Aerosp. Conf.*, vol. 2, pp. 403-414, 2000.
- [71] Bernard D., G. Dorais, E. Gamble, B. Kanefsky, J. Kurien, G. Man, W. Millar, N. Muscettola, P. Nayak, K. Rajan, N. Rouquette, B. Smith, W. Taylor, and Y.-W. Tung, Spacecraft autonomy flight experience: The DS1 remote agent experiment, in *Proc. AIAA*, Albuquerque, NM, pp. 28-30, 1999.
- [72] Durou O., V. Godet, L. Mangane, D.P. Peramaud, R. Roques. Hierarchical fault detection, isolation and recovery applied to COF and ATV avionics. *Acta Astronautica Vol. 50, No. 9, pp. 547-556*, 2002.
- [73] Ducard, G.J.J. Fault-Tolerant Flight Control and Guidance Systems for a Small Unmanned Aerial Vehicle. PhD Thesis, ETH Zurich, 2007.
- [74] Zolghadri A., Gheorghe A., Cieslak J., Henry D., Goupil P., Dayre R. and Le Berre H. A Model-based Solution to Robust and Early Detection of Control Surface Runaways. *SAE International Journal of Aerospace*, 4:1500-1505, November 2011. Lombaerts, T.J.J. Fault Tolerant Flight Control. A physical model approach. *PhD Thesis, TuDelft, Netherlands*, 2010.
- [75] Rotstein H.P., R. Ingvanson, T. Keviczky, G. J. Balas. Fault-Detection Design for Uninhabited Aerial Vehicles. *Journal of Guidance, Control, and Dynamics*, Vol. 29, No. 5, September-October, 2006.
- [76] http://en.wikipedia.org/wiki/Technology_readiness_level.
- [77] <http://addsafte.deimos-space.com>
- [78] ECSS 70-11A (2005) Space engineering: Space segment operability, European Cooperation for Space Standardization standard, 2005.
- [79] <http://www.nasa.gov/centers/ames/research/technology-onepagars/livingstone2-modelbased.html>.