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From theory to flight tests: Airbus Flight Control System TRL5 achievements

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Abstract: In this article, concrete aerospace industrial achievements corresponding to a level 5 on the Technological Readiness Level (TRL) scale are presented. Starting from basic research levels up to industrial validation, it is shown how it is possible to bridge the gap between advanced methods advocated by the academia and the more and more demanding industrial needs. To illustrate this position, a focus is made on real-time on-board Fault Detection and Diagnosis (FDD) for the upcoming and future innovative Flight Control System (FCS) of civil aircraft. This is exemplified by three concrete cases presenting the research and development process, from theory up to simulator and flight tests: 1) detection of Oscillatory Failure Cases in FCS thanks to a derivative-free variant of an extended Kalman filter; 2) detection of control surface lock-in-place failure (a.k.a. jamming) via recursive parametric modeling; 3) flight parameter Data Fusion with dedicated fuzzy logic.

Keywords: Aerospace Engineering, Industrial Applications, Flight Control System, Fault Detection and Diagnosis, Sensor Data Fusion.

1. INTRODUCTION

Control theory and control engineering have now reached a very high level of maturity in the sense that many practical applications have come into the world and changed our daily life. Control in space and aerospace related systems also exhibits many innovations that have revolutionized humankind, ranging from vehicle guidance navigation and control through health monitoring and diagnosis. However, there is still a large number of advanced techniques published in the literature that while promising have not yet been applied in an industrial real-world context. The image of an “application bottleneck” (or “dead-valley”) is eloquent and demonstrates that there is still a great effort to bridge the gap between the scientific methods advocated by the academia and the industrial needs (Figure 1).

The Technological Readiness Level (TRL) scale is a methodology widely spread internationally in the Industry to monitor maturity development of R&T Technology Products [1]. In an ever more competitive Business environment, the policy of companies is to deliver the most efficient, innovative product, considering customer needs. In this context, TRL tool is the reference to secure a harmonized methodology all across R&T Programs. Academia typically focuses on the low TRL levels, from 1 to 3, while industrial interest seriously starts at TRL level 5, where the demonstration of product properties with industrial needs can be initiated, until a maximum level of TRL9 representing the certification and real use of the products (Figure 3). It has been identified the need to bridge the gap between TRL3 and TRL5 for catalyzing the innovation in the Industry. This paper proposes an industrial view on this point, by focusing on real-time on-board Fault Detection and Diagnosis (FDD) for the upcoming and future innovative Flight Control System (FCS) of civil aircraft. Concretely, in this context, the industrial objective is to implement the desired innovation in the Flight Control Computer (FCC) of the aircraft once its compliance with stringent certification requirements has been proven. This demonstration is done after severe Verification and Validation (V&V) activities. Among all possible candidates, we will concentrate in this paper on model-based FDD solutions. Widely advocated by the academic community, most of these FDD advanced approaches rely on the idea of completed physical measurements with analytically computed redundant variables [2]. For example, a common method to analytically detect the existence of a failure is to look for anomalies in the plant's output relative to a model-based fault-free estimate of that output.

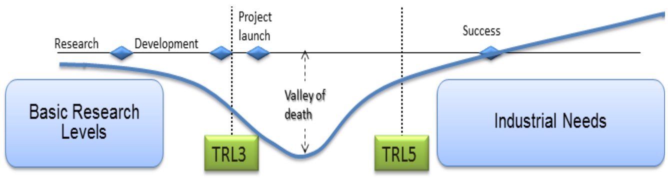

Figure 1: Industrial application bottleneck

This paper is organized as follows: in section 2, the stringent FCS development context is presented, highlighting some concrete industrial constraints to take into account. Section 3 suggests certain subjective rules to consider for successful cooperation, in view of the authors’ experience. Finally, section 4 is devoted to three concrete examples of fruitful collaborations, between Airbus design office and academic partners, which have reached an average TRL 5 achievement. Some conclusions and perspectives are proposed in the last section.

2. INDUSTRIAL CONTEXT: FLIGHT CONTROL SYSTEM DEVELOPEMNT

This section presents the context of FCS development and its very demanding environment, to make the reader sensitive to the main constraints to consider before converging towards a solution acceptable from the industrial point of view [3].

Civil aircraft FCS development is an arduous process because this system is critical in the sense that any severe malfunctions could potentially affect the flight or prevent its correct achievement in the optimum configuration (e.g. performance, fuel consumption). Most, but not all, of the design requirements come directly from the Aviation Authorities (for example Federal Aviation Administration in the US and European Aviation Safety Agency in Europe). Taking into account these regulations leads to develop FCC software according to the Design Assurance Level A, which is the most stringent requirement for real-time on-board software. It means e.g. that the person verifying the code may not be the person who developed it and this separation must be clearly documented. The FCC software is generally specified thanks to a graphical tool (SAO, for Computer Aided Specification) describing accurately all the functions to be ensured (e.g. sensor acquisition and monitoring, flight control laws computation). A limited set of graphical symbols (e.g. adder, filter, integrator, look-up tables, very much in the style of SIMULINK blocks) is used to describe each part of the algorithm. Then, the corresponding source code to be implemented in the FCC is automatically generated thanks to a dedicated tool. The limitations imposed by such a process guarantee on the one hand that the code has a complexity level which allows it to be implementable on the actual computer but on the other hand it makes the designer task more complex. As illustrated on Figure 2, a very simple one-block operation (matrix computation) under SIMULINK environment becomes cumbersome under SAO setting: the calculation must be broken down to a series of scalar multiplication and addition operations. This gives some insight into the coding complexity for real-time implementation. A contrario, this process offers many advantages [3], like for example the possibility to use parts of the specified code from one aircraft program to another.

The FDD design to be implemented on-board in real-time must provide high levels of robustness and performances. The unavoidable resulting trade-off could be difficult to establish. The robustness of an FDD design must not degrade the aircraft operational reliability (i.e. False Alarm rate lower than the FCC Mean Time Between Failure - MTBF). The probability of Missed Detection, as part of the design performance, is a function of the fault occurrence probability: the probability that the fault appears AND is not detected must be extremely improbable, that is, lower than 10^{-9}/flight hour. Guaranteeing both very low probabilities (False Alarm and Missed Detection) represents a stringent constraint.

The TRL process (Figure 3) is applied [1] to ensure R&T project spin-offs to be really used in an industrial product (e.g. an innovative FDD design in the FCC software) and to take into account the aforementioned limitations (computational load, robustness, criticality…). In this way, the risk to implement the innovation in an existing or new product is assessed. Beyond TRL5, the project can be considered as entering in its industrial phase. This means FDD design integration and validation in relevant environment, that is, its assessment within representative test facilities (e.g. actuator bench, flight simulator). Consequently, the V&V process is of primary interest to assess the viability and performances of the proposed designs. Significant V&V activities are performed all along the FCC development cycle (termed the "V-cycle") during severe test campaigns. Different kinds of simulators and test benches are used whose fidelity is complementary and allows exploring a wide range of pilot inputs, flight conditions and perturbations: desktop simulator (software coupled to an aircraft model), System Integration Bench (e.g. a grounded control surface equipped with actuators and controlled by a FCC), "Iron Bird" (a kind of "naked" aircraft, without the fuselage, the structure, etc..., but with all system equipments installed and powered as on a real aircraft), flight simulator (real aircraft cockpit coupled to an aircraft model or to the Iron Bird). The V-cycle ends with substantial flight tests performed on several aircraft fitted with "heavy" instrumentation. Preliminary to the V&V campaign, as part of the verification activities, peer reviews of the functional specifications and their justification are organized. This is done in light of the lessons learned by scrutinizing incidents that occur in airline service or during flight tests of the previous aircraft programmes. For obvious safety reasons, the faults are not injected during real flight tests but rather simulated off-line. To check the behavior of the aircraft when the control loop reacts to the faults, these latter are injected on the aforementioned high-fidelity closed-loop simulators.

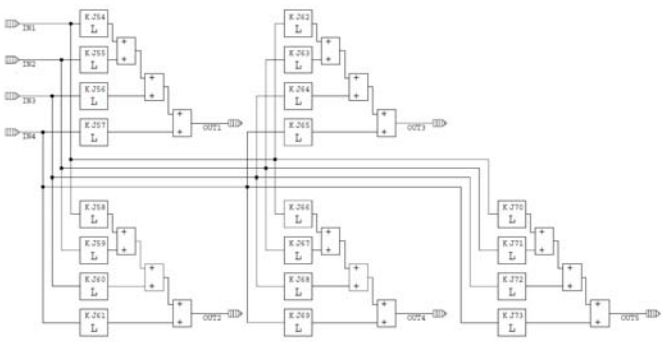

Figure 2: 5 × 4 matrix calculation example

3. RECIPE FOR SUCCESSFUL COLLABORATION

In this section, some golden rules are proposed for favoring successful aerospace collaborations, based on the authors' experience. This represents a limited subjective viewpoint and does not reflect in any case an official Airbus view. For other interesting perspectives the reader may also consult old and very recent papers dedicated to the same subject but concerning different applications: [4][5][6].

As a preliminary condition for fruitful industrial/academic cooperation, a **very close collaboration** is needed. These are two different worlds and time must be left to understand each environment, expectation and limitation, favoring for example face-to-face meetings especially at the beginning of the project. The scientific theme underlain by the industrial problem to tackle should fit well in the academic lab competences and interest. The proposed subject should also, if possible, open possibilities for basic scientific research. Some practical industrial problems, once deeply analyzed and formalized, could indeed revealed theoretical barriers that merit to be investigated [7]. In other words, the technical research problem should be pertinent to bridging the gap.

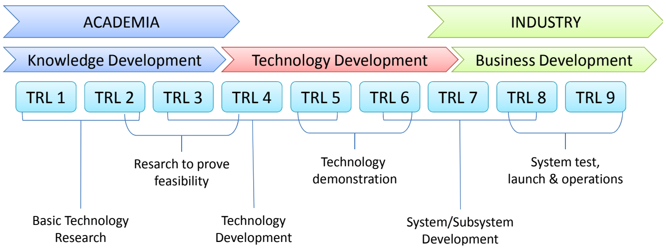

Figure 3: the TRL scale

A high level of engineering applicability is expected: a technologically viable solution demonstration must conclude the project (e.g. simulator session). It must be accompanied by an effort from the industrial to provide the academic labs with all necessary means and information. This means opening sufficiently the industrial state-of-practice, sharing best practices and above all providing high-fidelity **benchmarks**. In the context of this paper, “benchmark” means a high-fidelity aircraft model and representative fault scenarios. Providing only a single LTI model in the form of four constant state-space matrices would be antagonist to the industrial expectations. In some recent EU projects (ADDSAFE [9] and COFCLUO [10]), Airbus has provided the consortium with high-fidelity closed-loop nonlinear aircraft models [8] under Matlab/Simulink environment. They are greatly representative of generic civil commercial aircraft flight physics and handling qualities, including the nonlinear rigid-body model with a full set of control surfaces, actuator and sensor models, control laws and pilot inputs. It allows exploring the whole flight domain considering a wide class of pilot inputs and wind perturbations. It permits extensive simulation campaigns thanks for example to Monte-Carlo analysis. In a very recent EU FP7 project entitled RECONFIGURE it has been decided by Airbus to deliver to the consortium an even more representative non-linear in-flight validated model [11]. As stated in the introduction, model-based approaches are good candidates for innovative actuator and sensor FDD. Consequently, the dedicated models in the benchmark must be very close to the reality, including noise and uncertainties, otherwise the application on real aircraft would be compromised.

Based on author’s experience, the third rule to mention is to **be inspired by the state of practice** (if known). Instead of proposing first a completely disruptive solution, small improvements of the industrial solutions already in place could be a good practice [12]. It is also a very good way to understand well the problem to be solved. Then in a second step, a more innovative approach could be investigated.

Real-time and operational constraints for on-board implementation should be mentioned. Due to limited CPU capacity in FCC, the proposed solution computational load and design complexity should be limited (e.g. on-line optimization techniques are prohibited). Related to the complexity, an important issue is the need for clear, systematic and formalized guidelines for tuning of the design. The design method should provide high-level tuning parameters that can be used by non-expert industrial operators. Easy-tuning is also required when adapting the solution to a different context: e.g. another control surface or flight parameter sensor on the same aircraft, same context but on a different aircraft or even the combination of both (different sensor on a different aircraft type). The number of input parameters should be limited too in view of their tuning and also anticipating the V&V activities (especially in case of scheduling tuning parameters). Related to real-time constraints, an important aspect is the **convergence time**. This is of primary interest following an FCC in-flight reset, which is a possible normal operation from the pilot. If the FDD design takes too much time to converge towards a steady behavior, it could impact the FCC operational reliability. In the same order of idea, the long-term FDD design behavior must be assessed. A long range aircraft could indeed spend several hours in cruise phase without any control surface movement or without any noticeable flight parameter variations. Finally, from the operational viewpoint, the robustness of the proposed solution is of primary interest in order not to degrade the aircraft operational reliability. Any lack of robustness could dramatically impact the airliner economical profitability. Thus, for FDD designs, the required False Alarm rate must be validated in nominal and in degraded configurations. The Missed Detection rate must also be carefully assessed because of the possible fault consequences. In both cases, very low probabilities have to be managed.

Finally, to assess the viability, performance and robustness of the proposed designs, **comprehensive V&V activities** must be performed. A simple validation on a case study is not sufficient and should be accompanied e.g. by Monte-Carlo and worst case analysis. An aircraft is subject to a wide range of operational conditions and external perturbations so it is required to assess that the required performance and robustness are achievable for all possible aircraft operating points.

4. CONCRETE TRL5 ACHIEVEMENTS

This section is devoted to some concrete examples of successful Airbus cooperation with academia which have reached, or are going to reach in the coming months, a TRL level 5, that is, implementation in FCC of the selected solution for simulator or even flight tests. They concern sensor and actuator FDD in FCS for upcoming and future aircraft. Rarely broached in the literature in the past decades but more recently the subject of projects involving academic and industrial partners [9][13], it is now recognized and demonstrated that advanced FDD can contribute to the future more sustainable aircraft by enhancing its structural design (resulting in weight saving), which in turn helps increase aircraft performance and to optimize its environmental footprint (e.g. fuel consumption and noise). On the other hand, the need to extend guidance and control functionalities has been identified to assist the pilot and making the flight task easier [11]. This could be accomplished thanks to innovative data fusion supporting sensor FDD. These two objectives are illustrated below.

4.1 Oscillatory Failure Case detection

Spurious oscillating signals propagating through the control loop of an aircraft moving surface can lead to additional load on the structure when located within the actuator bandwidth [3]. Early and robust detection of these Oscillatory Failure Cases (OFC) allows optimizing the structural design and thus contributes to save weight. OFC detection on-board the A380 has been solved thanks to a simple model-based approach (residual generation and decision making) which is now certified and applied on in-service aircraft [14]. In collaboration with the University of Bordeaux, France, a close-loop and adaptive version of this technique has been developed to achieve better performances. As mentioned in section 3, being inspired by the proven state of the art could be a good practice. This is why it has been decided to use the same approach, keeping the same decision making step and the same model, while improving the quality of the actuator model in order to decrease the residual energy and thus to detect smaller OFC. Among several candidates a derivative-free variant of an Extended Kalman Filter (EKF) has been applied. This nonlinear local filter allows estimating jointly the system state (actuator position) and the actuator model varying parameters based on the Divided Difference mechanism [15]. The estimated augmented state vector is updated at each FCC sampling time. An important problem with EKF is to tune properly the high level design (hyper) parameters which control the bandwidth of the filter. This problem is solved in [16] where a systematic procedure is derived. The FCC implementation is eased by the choice of a derivative-free variant which allows alleviating the computation load thanks to function evaluation and also by a wise choice of the parameters to estimate leading to some calculation simplifications. The whole strategy (nonlinear filtering coupled to the state of practice decision making) has been first assessed on A380 test facilities before being implemented and used on the latest Airbus model, the A350 XWB. Figure 4 shows some residual examples during ground tests (Iron Bird) and flight tests (calibrated airspeed Vcas=245 kts) when high dynamic commands are applied on the Rudder control surface. For industrial reasons the plots have been normalized. The benefit of the proposed strategy is clearly exhibited on fault-free signals. A great attention is also paid to check that the faults are also detectable during off-line tests. It has been validated that the performance can be increased by 50%, which means that the minimum detectable failure amplitude is divided by two, while keeping robustness compliant with operational requirements.

4.2 Control surface jamming detection

A jamming (a.k.a. lock-in-place failure) is an abnormal situation where a control surface is stuck at its current position after a mechanical or electronic malfunction. Under some circumstances, it can create additional loads on the structure or impair the aircraft control. A fruitful collaborative effort between Airbus and the University of Bordeaux, France, allowed developing a portfolio of present-day and advanced designs to tackle the jamming detection at any control surface deflection, including the null position. The industrial state of practice consists in generating an error signal by comparing redundant signals in the FCC followed by threshold-based decision making [13]. Two examples of improvements are described in this section, from simple to a more complex solution, illustrating one of the rules proposed in section 3, that is, being inspired by the industrial practices.

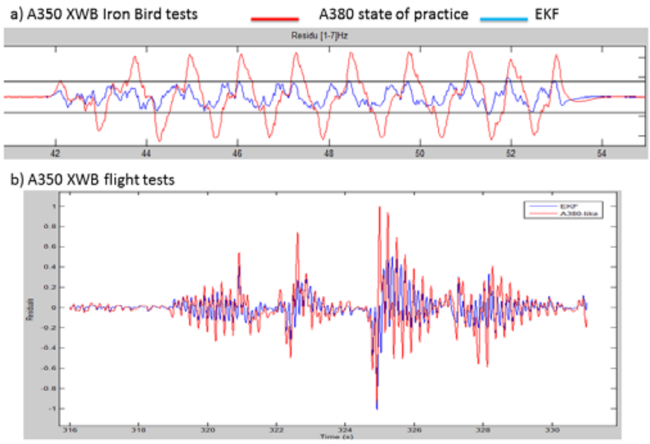

Figure 4: OFC detection via EKF on the A350 XWB

The first strategy keeps the same state-of-the-art basic principle complemented by a dedicated Kalman filter inserted between residual generation and decision making [13]. The in-service residual evaluation block is preserved due to its simplicity, reliability and proven efficiency. Concretely, a 2^{nd} order Kalman filter is synthesized off-line. The optimization of its two tuning parameters is performed within a "model matching" setting by using an appropriate target response. The whole strategy has been assessed on Airbus aircraft model [8], off-line real data sets and even during flight tests (15 A380 flights representing 70 hours for robustness validation only). It is confirmed that the proposed solution allows to decrease the in-service threshold by 50% and so to decrease the minimum detectable jamming position [13] [17].

The second strategy is a disruptive solution compared to the state of the art. It consists in recursive parameter estimation of the control surface servo-loop single-input (the pilot order) single-output (the control surface position) dynamic system [17]. The unknown time-varying parameters are estimated via the exponential forgetting algorithm. A second order model structure is chosen for compliance with computational power limitation. When a jamming occurs, it can be demonstrated that one of the estimated parameters converges towards zero. This abrupt change is an indicator of the jamming and can be confirmed thanks to a simple threshold-based logic or via a more advanced two confidence region decision test (so-called "CR2"). For real-time implementation in the FCC, some fine-tuning allows to prevent covariance "wind-up" and numerical instability problems. V&V activities on real data sets, benchmark and simulators have shown that the proposed method allows control surface jamming detection at small amplitudes and even around the null position (with a non-zero command) [17].

4.3 Sensor data fusion

The flight control law computation requires the availability of accurate and reliable flight parameters which are typically measured by 3 redundant sensors of the same technology. Before feeding the control law computation, an upstream processing is needed: to choose or to compute a single value from the 3 inputs and in parallel to monitor each measurement to discard any faulty signals. This sensor management system is termed "consolidation" (Figure 5) or flight parameter data fusion [3]. A majority voting scheme is generally practiced in the industry and is considered as a proven technology in modern FCS [18]. However, in order to extend Guidance and Control functionalities for future aircraft [11], it could be required to prolong as well the flight parameter availability. This can be done thanks to estimators (so-called "virtual sensors"). Assuming that 3 physical measurements can be complemented by 2 dissimilar virtual sensors the current industrial state of practice could be unsuitable (Figure 5). Fuzzy logic techniques, widely used in other industrial areas, could be a good candidate. In collaboration with an academic signal processing lab (Telecommunications for Space and Aeronautics, www.tesa.prd.fr), Airbus has developed such a solution assuming the fault modes are dissimilar between real measurements FP_i ($i=1,2,3$) and each virtual sensor V_i ($i=1,2$). The first step consists in computing a fuzzy weight w in function of the distance between a virtual sensor and a physical measurement, e.g.:

$$w_1=1 \text{ if } |FP_1-V_1|<T_1$$
$$w_1=0 \text{ if } |FP_1-V_1|>T_2$$
$$w_1=a|FP_1-V_1|+b \text{ if } T_1<|FP_1-V_1|<T_2$$

T_1 and T_2 are two thresholds defining the validity region (Figure 6). The same computation is done for each measurement compared to each estimator. In the second step, thanks to this weighting function it is possible to define fuzzy rules to estimate the coherency between measurements and estimators, e.g. "if FP_1 is coherent with V_1 AND FP_1 is coherent with V_2" OR "if FP_1 is coherent with V_1" OR "if FP_1 is coherent with V_2" then FP_1 is valid. This coherency rule is written like a binary decision but in fact it must be understood as a fuzzy decision. It means that the degree of coherency is neither 0 nor 1 but rather a fuzzy function of the distance between FP_i and V_i. The "AND" and "OR" are fuzzy operators (e.g. Lukasiewicz operators [18]). The third step consists in computing a score S_i for each sensor FP_i. It can be viewed as the mathematical translation of the literal definition of the rule, using the operator definition. And finally, in the last step, the consolidated parameter is computed as the following linear combination:

$$FP_c = \sum_{i=1}^{8} \beta_i c_i$$

Where β_i is the product of the three scores S_i when considering all possibilities: 3 correct measurements, 2 correct measurements and 1 erroneous, 1 correct measurement and 2 erroneous or 3 erroneous measurements. For example, in the first case it is proposed to use $\beta_1 = S_1 \times S_2 \times S_3$, in the 2nd case $\beta_2 = S_1 \times S_2 \times (1-S_3)$ and in the last case $\beta_8 = (1-S_1)\times(1-S_2)\times(1-S_3)$. This leads to 8 different possibilities. For each β_i, there is then a different definition of c_i:

- 3 valid sensors, $\beta_1 = 1$, c_1=median(FP_i)
- 2 valid sensors, $\beta_i = 1\,(i = 2,3,4)$, c_i = average(FP_j) with j={1,2} or {1,3} or {2,3}.
- 1 valid sensor, $\beta_i = 1\,(i = 5,6,7)$, c_i = FP_j with j=1,2 or 3.
- No valid sensor, $\beta_8 = 1$, c_i= V_1 or V_2.

Let us remark that $\sum_{i=1}^{8} \beta_i = 1$ and that the β_i are exclusive (only one is equal to 1) with a smooth transition from one β_i to the other in case of fault occurrence.

Figure 7 shows an example on a case study (real in-flight data set): on the top, 2 of the 3 aircraft speed measurements become faulty (full runaway of Vc_1 and Vc_2) at t=3255. Two virtual sensors $Vcest_1$ and $Vcest_2$ remain correct and close to the last valid air data sensor (Vc_3). The state of practice (vote) would lead to an erroneous consolidated value. Thanks to the two estimators and to the proposed fuzzy logic (at the bottom of Figure 7), after a slight transient runaway, the remaining correct sensor measurement is selected at the end. One can also notice that once the faults disappear (t=3350), the two corresponding measurements are automatically injected in the consolidation process.

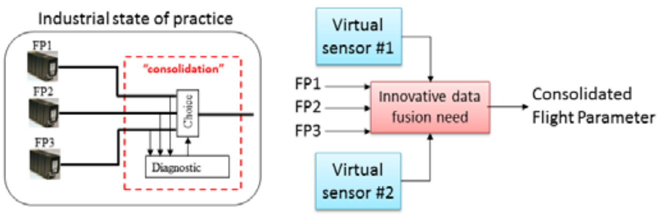

Figure 5: industrial consolidation (left) and the need for innovative Flight Parameter (FP) data fusion (right).

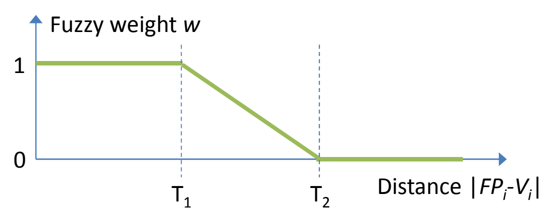

Figure 6: fuzzy weighting function for data fusion

5. CONCLUSION

In the FCS development context, and especially for FDD issues, bridging the gap between academia and industry is requied. There is a clear need to accompany the new societal imperatives towards a greener and easier-to-handle aircraft. The industrial state of practice is no more suitable as it would lead to additional weight, cost and complexity.

This article is an attempt to show that fruitful cooperation between academia and industry is possible and even suitable to bring innovation in manufacturing products. Based on the authors' experience some golden rules are suggested. They do not pretend to be exhaustive and certainly merit to be completed with other experiences. Some appealing avenues could be mentioned for future works. The academic solutions must be as generic as possible, in order to be applied on different but similar systems (e.g. different actuators and sensors). The high-level tuning is of primary interest: it must be simplified to shorten the V&V activities and to support the aforementioned genericity. A lack of tuning methods has been identified and could be the topic of future works. Improving the state of practice with very simple solutions seems challenging, so more and more complex solutions should be envisaged. The inherent complexity must be well mastered by the industrial.

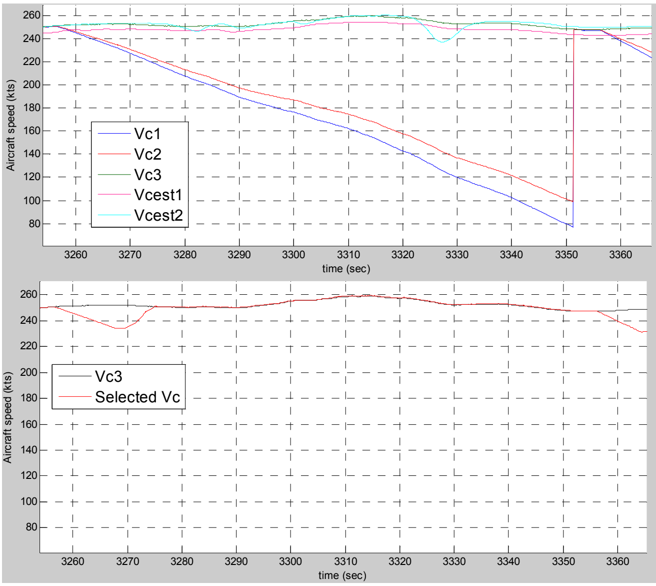

Figure 7: fuzzy logic used for aircraft speed consolidation.

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