Report on EU/IEEE-CSS Workshop on Industrial and Academic Experience in Aerospace Fault Detection and Diagnosis

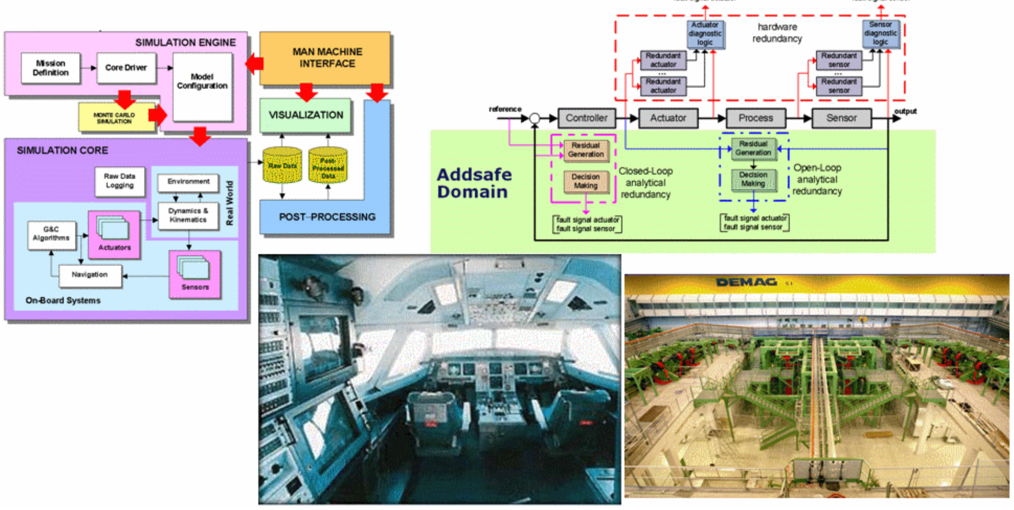
EU/IEEE Workshop on Industrial and Academic Experience in Aerospace Fault Detection and Diagnosis (FDD)

Airbus, Toulouse (France) 23rd-26th October 2012

.

ADDSAFE

Advanced Fault Diagnosis for Sustainable Flight Guidance and Control



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CONTENT LIST

1 IEEE-CSS OUTREACH PROPOSAL MOTIVATION & OBJECTIVES

An ***International EU/IEEE Workshop on "Industrial and Academic Experience in Aerospace Fault Detection and Diagnosis"*** was organized with funding from the IEEE Control Systems Society (CSS) Outreach Fund and all the partners from the European 7th Framework project "Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE)".

The workshop was held at Airbus facilities in Toulouse (France) on the 23rd-26th October 2012 and gathered 55 attendees and 29 technical speakers from academia, research labs, European industries and authorities. The organizers of the workshop were:

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1.1 MOTIVATION

The state-of-practice for aerospace manufacturers in diagnosis of guidance and control (G&C) faults is to provide high levels of hardware redundancy in order to perform coherency tests and ensure sufficient available control action. This approach is well mastered and fits perfectly into current aircraft certification processes while ensuring the highest level of safety standards. However, the consequence of this hardware redundancy based diagnosis is an increase of the aircraft weight and complexity as well as of its manufacturing and maintenance costs. Furthermore, the new technologies being developed today for optimizing the aerospace system performance are challenging the current approach and thus the aerospace industry has started to look into alternate solutions.

Advanced Fault Detection and Diagnosis (FDD) techniques, especially those termed analytical or model-based, have been proposed by academia as a way to alleviate the above issues and improve the diagnosis performance in the face of nonlinear and uncertain conditions for the last 20 years. Despite achieving a high theoretical maturity stage, and also a high practical readiness level in other domains, they have not found major supporting ground in the aerospace commercial field. This has been the case mostly due to: (i) the inherent cost/effective trade-offs performed by industry; (ii) the specific implementation and certification issues faced in designing and deploying operational FDD systems; (iii) lack of focused communication, understanding and exchange of information between academic representatives and industrial stakeholders; and (iv) lack of technological demonstration using industrial-level benchmarks and V&V processes.

Thus, a dedicated forum where the industrial specialists responsible for designing, validating and deploying these technologies share their concerns and lessons learnt with an academic audience in exchange for exposition to the technical research and development status of the techniques will go great strides to create a critical mass for:

- The transfer of the techniques to aerospace industrial groups
- The understanding of the industrial issues by the research/university groups
- The establishment of future collaborations among industrial and research groups

1.2 GOAL AND OBJECTIVES

The goal of the proposal to the IEEE-CSS Outreach Fund was to organize a two-day event to serve as a forum between aerospace FDD academia and industry practitioners. The workshop was to be held after the final meeting of the European Union 7th Framework Program ADDSAFE project (see Section 3) but corresponding technical presentations of the project and especially the final demonstration was to form part of the workshop.

The invited roster was to be formed by recognized international experts in the control-FDD domain from academia and the aerospace industry, representatives from international/national funding and research agencies as well as representatives from civil certification authorities.

The objectives of the workshop were then:

i. *To provide a focused forum for the understanding of the current state-of-practice (by industry) and state-of-art (by academia) in the aerospace FDD domain*.

   For example, a subject rarely broached in the academic literature but fundamental for aeronautical industrial groups is the link between aircraft sustainability and fault detection. Indeed, it can be demonstrated that improving the performance of FDD allows optimizing the aircraft structural design (weight saving) with resulting improvements in aircraft performance and a decrease of its environmental footprint. Thus, advanced FDD for early and robust detection of small amplitude faults becomes of primary interest for the development of the future sustainable aircraft (cleaner, quieter, smarter and more affordable) but academia was not aware until recently of this important argument for the techniques

ii. *To support IEEE CSS outreach activities in terms of academia-industry*

   It order to achieve this outreach activity Airbus will use its very good contacts through the EADS group and its R&D experts network with other major EU aircraft manufacturers while similarly, Deimos Space will tap into its extensive contacts with EU space companies. Thus, it is assured that the workshop audience will be exposed to a wide technical view of the industrial problematic in aerospace FDD favouring an exposition and interchange of information with experts typically outside the standard academic conference circuits.

iii. *To be exposed to the final results and lessons learnt from the EU-FP7 ADDSAFE project*.

   This will facilitate also the understanding of the industrial problematic as well as show the industrialization process (from theoretical to application and validation) for a wide plethora of advanced FDD methods. Further, the access of the audience to the final demonstration of the project will allow them to view Airbus testing facilities otherwise restricted to the general public and see firsthand the V&V processes used by industry to assess the plausibility of advanced methods (and improve their understanding on the reasons for the slow and sometimes painful adoption of the proposed methods).

2 EU/IEEE WORKSHOP ON INDUSTRIAL AND ACADEMIC EXPERIENCE IN AEROSPACE FAULT DETECTION & DIAGNOSIS

2.1 SUMMARY

The funding from the IEEE-CSS Outreach Fund together that from the partners of the EU-FP7 ADDSAFE project served to organize an international EU/IEEE Workshop on ***"Industrial and Academic Experience in Aerospace Fault Detection and Diagnosis"***. The event was organized by Dr. Andrés Marcos (DEIMOS) and Dr. Philippe Goupil (AIRBUS) at Airbus facilities in Toulouse, and was held from the 23rd to the 26th October 2012.

Following the IEEE-CSS proposal, the workshop was devoted to the FDD practices in Aerospace with the goal of serving as a forum between aerospace FDD experts from industry and academia as well as to present the final results of the ADDSAFE project and their demonstration on Airbus V&V facilities.

Figure 2-1 EU/IEEE-CSS Workshop: group picture

The workshop gathered 55 attendees from academia (Universities from England, France, Netherlands, Hungary, Germany, USA), research centers (ONERA, DLR, CNRS, CIRA, CNES), European industries (Astrium, Eurocopter, EADS Innovative Works, Airbus, Deimos) and authorities (EASA, NASA, ESA). Both sides, academic and industrial, were very well represented and balanced as indicated in Figure 2-2.

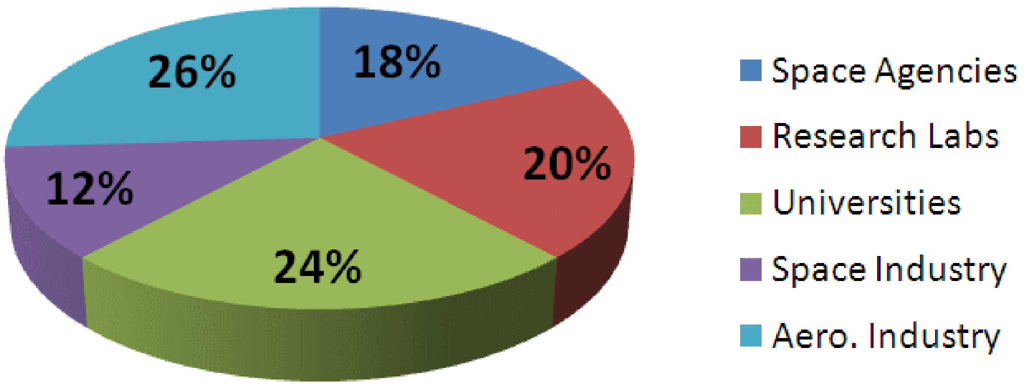


Figure 2-2 EU/IEEE-CSS Workshop on FDD: attendance statistics

In addition, there were five high-caliber plenary speakers and 25 technical speakers covering the Space and Aeronautic domains. The presented technical talks covered from currently deployed FDIR systems (Automated Transfer Vehicle, Airbus' aircraft or scientific satellites such as CNES Pleiades) to certification issues and specific advanced technological developments in the FDD field. The schedule of the talks is given in Figure 2-3 and the rooster of speakers and attendees in Table 1

	RECEPTION & VISIT		ADDSAFE PROJECT		APPLICATIONS & THEORY		AGENCIES & VISIONS
	Tuesday		Wednesday		Thursday		Friday
		8:30 - 8:40	Welcome to Workshop				
		8:40 - 9:00	Welcome to Airbus				
		9:00 - 9:25	ADDSAFE: project - A.Marcos (DEIMOS)	9:00 - 9:25	Peter Seiler (UMN)	9:00 - 9:45	Plenary (NASA Langley)
		9:25 - 9:50	ADDSAFE: V&V - P.Goupil (AIRBUS)	9:25 - 9:50	Max Massimi (Eurocopter)	9:45 - 10:10	Benoit Frapard (ASTRIUM)
		9:50 - 10:15	coffee	9:50 - 10:15	Simon Hecker (U.Munich)	10:10 - 10:35	Pierre Viallefont (CNES)
		10:15 - 10:40	ADDSAFE: A.Varga (DLR)	10:15 - 10:30	coffee	10:40 - 10:50	coffee
		10:40 - 11:05	ADDSAFE: R.Patton (UHULL)	10:30 - 10:55	Edward Balaban (NASA Ames)	10:50 - 11:35	Plenary (ESA)
		11:05 - 11:30	ADDSAFE: C.Edwards (ULEIC)	10:55 - 11:20	Eric Bornschlegl (ESA-ESTEC)	11:35 - 12:00	Giovanni Cuciniello (CIRA)
		11:30 - 11:55	ADDSAFE: A.Zolghadri (CNRS)	11:20 - 12:00	Plenary (AIRBUS)	12:00 - 12:25	Johann Bals (DLR)
		11:55 - 12:20	ADDSAFE: Q.P.Chu (UDELFT)	12:00 - 12:25	Hafid Smaili (NLR)	12:25 - 12:50	Patrick Fabiani (ONERA)
		12:25 - 13:25	lunch	12:25 - 13:25	lunch	12:50 - 13:00	Conclusion (PG & ANME)
		13:25 - 13:50	ADDSAFE: B.Vanek (SZTAKI)	13:25 - 13:50	Alex Falcoz (Astrium Satellites)	13:00 - 14:30	Farewell Lunch
		13:50 - 14:15	ADDSAFE: A.Marcos (DEIMOS)	13:50 - 14:15	Carsten Doll (ONERA)		
		14:15 - 14:40	Bruno Cavrois (Astrium Launchers)	14:15 - 14:40	J.A. Mulder (Udelft)		
		14:40 - 14:50	coffee	14:40 - 15:05	Vicent Feuillard (EADS IW)		
		14:50 - 15:35	Plenary (DEIMOS)	15:05 - 15:30	Jozsef Bokor (SZTAKI)		
15:15 - 15:30	At A380 FAL security office	15:35 - 18:30	ADDSAFE DEMO	15:30 - 15:45	coffee		
15:35 - 18:30	Visit to Airbus A380 Facility			15:45 - 16:30	Plenary (EASA)		
20:30 - 22:00	Welcome Dinner						

Figure 2-3 EU/IEEE-CSS Workshop on FDD: schedule

The ADDASFE demo was performed during the course of an afternoon by AIRBUS' V&V team in their industrial test-benches (used prior to flight test and involving all the SW and HW avionics) in presence of the attendees and successfully showed the high technological readiness level (a TRL of up to 6) achieved by the developed designs in ADDSAFE.

Table 1 EU/IEEE-CSS Workshop: plenary speakers (green-shaded), technical speakers (grey-shaded) and attendees (blue-shaded)

Name	Affiliation	Type organization	Country
Christine Belcastro	NASA Langley	Space Agency	United States
Augusto Caramagno	DEIMOS SPACE S.L.U.	Space Industry	Spain
Michel Comes	AIRBUS	Aeronautics Industry	France
Eike Kircher	ESA-ESTEC	Space Agency	EU
Michael Weiler	EASA	Certification Agency	Germany
Edward Balaban	NASA Ames	Space Agency	United States
Johann Bals	DLR	Space Agency	Germnay
Prof. Jósef Bokor	SZTAKI	Research Agency	Hungary
Bruno Cavrois	ASTRIUM Launcher	Space Industry	France
Prof. Q.P. Chu	University of Delft	University	The Netherlands
Giovanni Cuciniello	CIRA	Space Agency	Italy
Carsten Döll	ONERA	Research Agency	France
Prof. Chris Edwards	University of Leicester	University	United Kingdom
Patrick Fabiani	ONERA	Research Agency	France
Alex Falcoz	ASTRIUM Satellites	Space Industry	France
Vicent Feuillard	EADS Innovation Works	Aeronautical Industry	France
Benoit Frapard	EADS Astrium	Space Industry	France
Philippe Goupil	AIRBUS	Aeronautical Industry	France
Prof. Simon Hecker	University Applied Sciences Munich	University	Germany
Max Massimi	EUROCOPTER	Aeronautics Industry	France
Andrés Marcos	DEIMOS SPACE S.L.U.	Space Industry	Spain
Prof. J.A. Mulder	Delft Technical University	University	The Netherlands
Eric Bornschlegl	ESA-ESTEC	Space Agency	The Netherlands
Prof. Ron J. Patton	University of Hull	University	United Kingdom
Prof. Peter Seiler	University of Minnesota	University	United States
Hafid Smaili	NLR	Space Agency	The Netherlands
Balint Vanek	SZTAKI	Research Agency	Hungary
Andreas Varga	DLR	Space Agency	Germany
Pierre Viallefont	CNES	Space Agency	France
Prof. Ali Zolghadri	CNRS-IMS /University Bordeaux	Research Agency	France
Halim Alwi	University of Leicester	University	United Kingdom
Dominique Chatrenet	AIRBUS	Aeronautical Industry	France
Lejun Chen	University of Hull	University	United Kingdom
Jerome Cieslak	CNRS-IMS /University Bordeaux	Research Agency	France
András Edelmayer	SZTAKI	Research Agency	Hungary
Laurens Van Eykeren	Delft Technical University	University	The Netherlands
Alain Fastre	AEROCONSEIL	Aeronautical Industry	France
Gilles Ferreres	ONERA	Research Agency	France
Joao Frota	AEROCONSEIL	Aeronautical Industry	France
Sharon Graves	NASA Langley	Space Agency	United States
Georges Hardier	ONERA	Research Agency	France
David Henry	CNRS-IMS /University Bordeaux	Research Agency	France
Xavier Loiseau	AEROCONSEIL	Aeronautical Industry	France
Daniel Ossmann	DLR	Space Agency	Germany
Luis F. Peñín	DEIMOS SPACE S.L.U.	Space Industry	Spain
Guilhem Puyou	AIRBUS	Aeronautical Industry	France
Germain Sabot	AIRBUS	Aeronautical Industry	France
Cedric Seren	ONERA	Research Agency	France
Xiaoyu Sun	University of Hull	University	United Kingdom
Laia Vilalta Estrada	AEROCONSEIL	Aeronautical Industry	France

2.2 TECHNICAL & PLENARY TALKS

The workshop started on Tuesday 23rd October with a visit to Airbus A380 Facilities and the welcome dinner. During the visit the workshop attendees where toured around the A380 final assembly line, see Figure 2-4, at the J.L. Lagardère site in Toulouse-Blagnac.

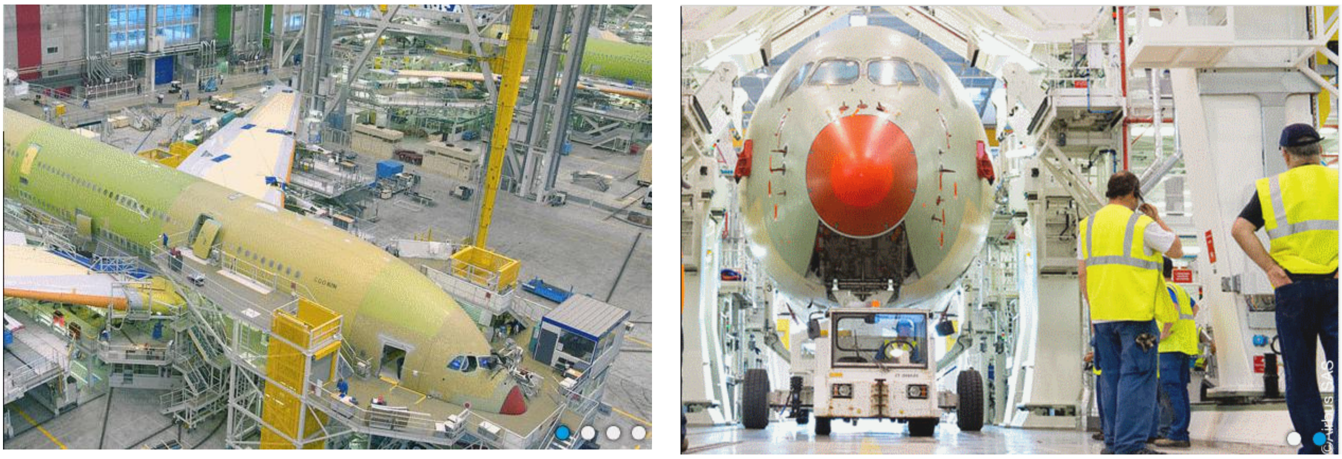


Figure 2-4 A380 Facilities: courtesy of Groupe Manatour (http://www.manatour.fr/Visit-Airbus-A380-Tour)

The technical schedule of talks covered the next two days and a half and was divided into:

- **1st day**: Welcome and ADDSAFE project presentations
- **2nd day**: Aerospace FDD Applications & Theory
- **3rd day**: Agencies & Visions

For the first day of talks, the focus was on the technical presentation of the results from the ADDSAFE project and its demo, see Table 2 (for some more details on the results see Section 3).

Table 2 EU/IEEE-CSS Workshops on FDD: 1st day presentations "ADDSAFE project"

Time	Speaker & Organization	Title
08:30-08:40	A.Marcos (Deimos) & P.Goupil (Airbus)	Welcome to Workshop
08:40-09:00	Vincent Rivron (Airbus)	Welcome to Airbus
09:00-09:25	A.Marcos (Deimos)	ADDSAFE project presentation
09:25-09:50	P.Goupil (Airbus)	ADDSAFE Airbus benchmark and V&V
10:15-10:40	A.Varga (DLR)	Synthesis of robust LPV FDD systems for monitoring flight actuator faults
10:40-11:05	R.Patton (Univ. Hull)	A Mixed H-/H∞ reference-actual LPV fault estimator for ADDSAFE
11:05-11:30	C.Edwards (Univ. Leicester)	Validation of Sliding Mode Observer FDI Schemes on ADDSAFE
11:30-11:55	A.Zolgahdri (U.Bordeaux-CNRS/IMS)	ADDSAFE Bordeaux: From theory to real-.time implementation and tests
11:55-12:20	Q.P.Chu (Univ. Delft)	Sensor Fault Detection A Physical Model Approach
13:25-13:50	B.Vanek (SZTAKI)	Bridging the Gap Between Theory and Practice in LPV FDI
13:50-14:15	A.Marcos (Deimos)	ADDSAFE Deimos activities: H∞ FDD design
14:15-14:40	B.Cavrois (Astrium launchers)	ATV FDIR: A system to ensure ISS safety and mission success
14:50-15:35	A.Caramagno (Deimos)	Deimos activities in Aerospace FDIR

The demo was performed after Deimos' plenary talk. For the demonstration the attendees were divided in two groups each one alternatively attending a demo on the real aircraft actuator benches (Figure 2-5) and a demo on the flight simulator (Figure 2-6). The Airbus V&V team showed in the industrial-level test benches (used prior to flight test and involving all the SW and HW avionics) the validity of the techniques studied during ADDSAFE. An example of the validation in the flight simulator is given in Figure 3. The demonstration showed the high technological readiness level (a TRL of up to 6) achieved by the designs.

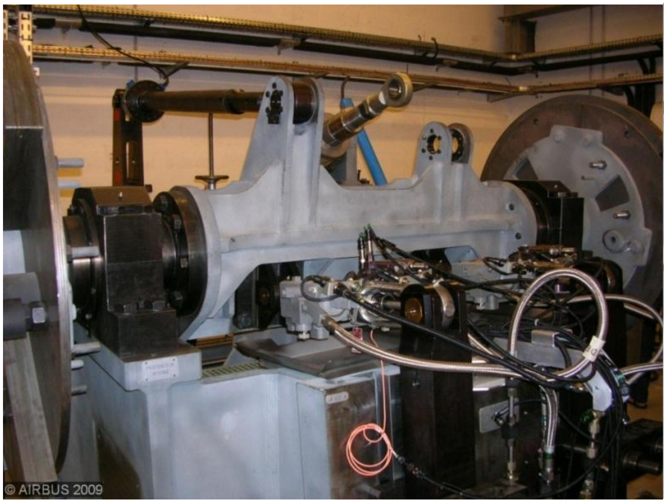


Figure 2-5: Airbus V&V facilities, an actuator bench.

Figure 2-6: Airbus V&V facilities, a flight simulator

Figures courtesy of Airbus (do not use without written permission)

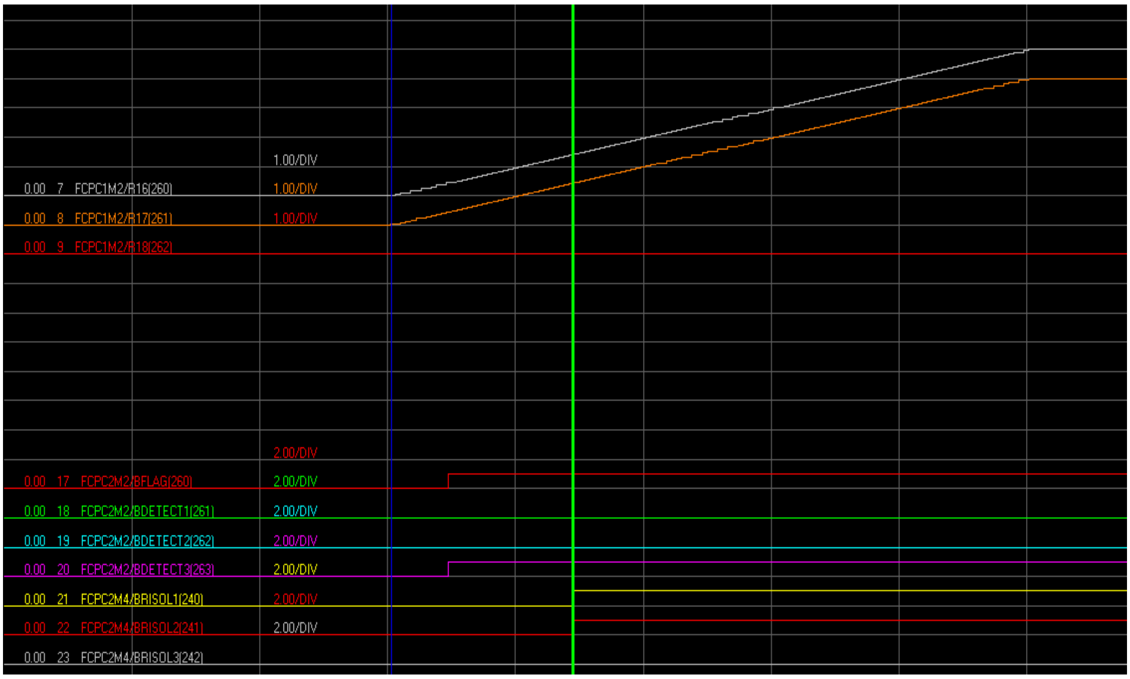


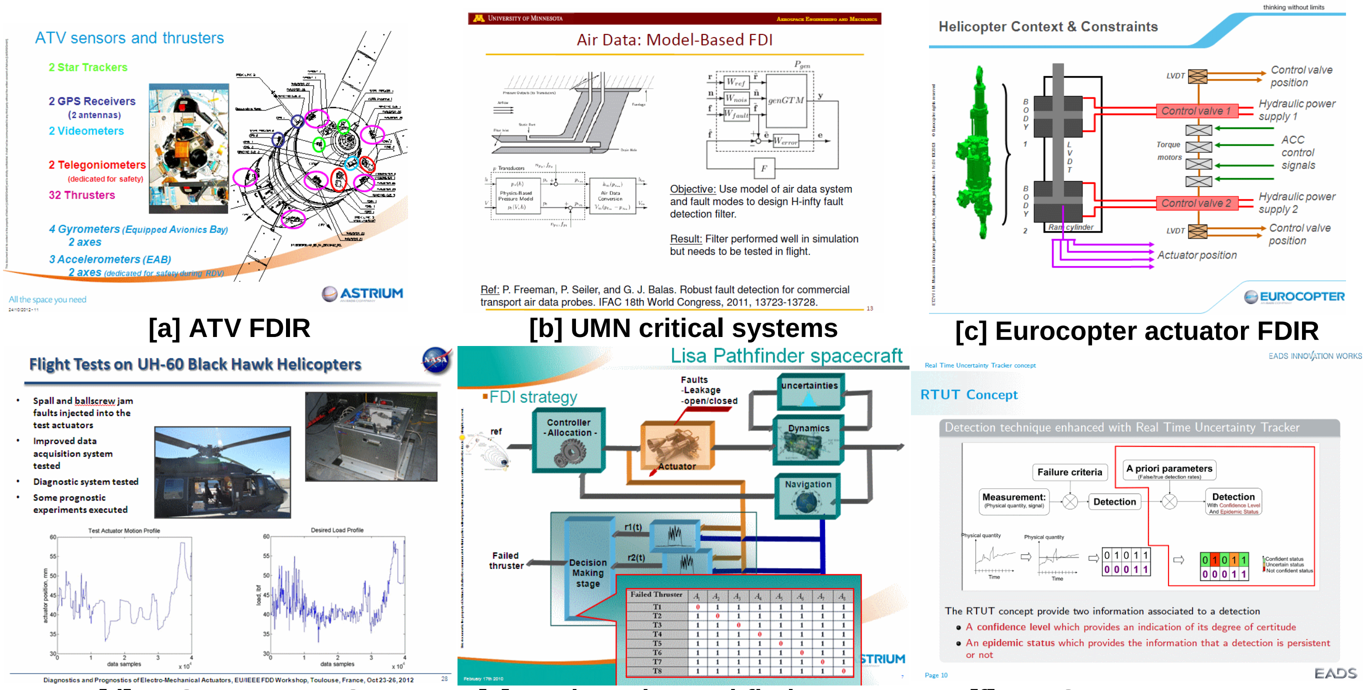
Figure 2-7 EU/IEEE-CSS Workshop on FDD: an example of results displayed during the demo

The 2nd day of the workshop was dedicated to the technical presentations from experts in academia, research labs and other organizations in terms of theory and practice, see Table 3.

Table 3 EU/IEEE-CSS Workshops on FDD: 2nd day presentations “Applications & Theory”

Time	Speaker & Organization	Title
09:00-09:25	Peter Seiler (Univ. Minnesota)	Design and Analysis of Safety Critical Systems
09:25-09:50	Max Massimim (Eurocopter)	Helicopter Problematic for Flight Control System FDIR
09:50-10:15	Simon Hecker (Univ. Munich)	LPV Model Generation for the ADDSAFE Benchmark
10:30-10:55	Edward Balaban (NASA Ames)	Diagnostic and Prognostic of Electro-Mechanical-Actuators
10:55-11:20	Eric Bornschlegl (ESA-ESTEC)	ESA R&D: Advanced FDI and FTC
11:20-12:00	Michel Comes (Airbus)	AIRBUS R&D activities & future
12:00-12:25	Hafid Smaili (NLR)	Aircraft Loss-of-Control Prevention from a Training & Flight Control perspective
13:25-13:50	Alex Flacoz (Astrium Satellites)	Modern Control Techniques Applied to Satellite FDIR
13:50-14:15	Carsten Döll (ONERA)	An Overview of FDI/FTC approaches investigated during the IMMUNE project
14:15-14:40	J.A. Mulder (Univ. Delft)	Future perspective of Aerospace FDD: On global health monitoring
14:40-15:05	Vincent Feuillard (EADS IW)	Real-time uncertainty tracker for anomaly detection in a diagnosis context
15:05-15:30	Jozsef Bokor (STZAKI)	Flight test platform for min-UAS insertion in the airspace: safety critical avionics
15:45-16:30	Michael Weiler (EASA)	Certification Aspects of Fault Detection and Diagnosis

Among the technical talks we had the first day: presentations from ADDSAFE by all the partners plus one by Bruno Cavrois (EADS-Astrium responsible for the Automated Transfer Vehicle flight control system) on the actual ATV FDIR implementation, see Figure 2-8-[a]. Then, on the 2nd day we had presentations by: Peter Seiler (University of Minnesota) on model-based methods for design and certification of safety critical flight controllers, Figure 2-8-[b], Max Massimi (fly-by-wire system leader at Eurocopter) on the challenges for advanced FDD in the context of helicopters, Figure 2-8-[c], Edward Balaban (NASA Ames senior researcher) on diagnostics and prognostic for electro-mechanical-actuators and their flight testing on an UH60 Blackhawk helicopter prepared for EMA FDD validation, Figure 2-8-[d], Alex Falcoz (FDIR expert at Astrium Satellites) presenting results from an ESA project on modern control techniques for satellites, Figure 2-8-[e], and Vincent Feulliard from EADS Innovative Works presenting results from an internal EADS R&D project at Airbus entitled Total Maintenance Operations Solutions & Technologies (MOST).



[a] ATV FDIR [b] UMN critical systems [c] Eurocopter actuator FDIR

[d] NASA Ames HMS [e] Astrium Lisa-Pathfinder FDIR [f] EADS IW RTUT concept

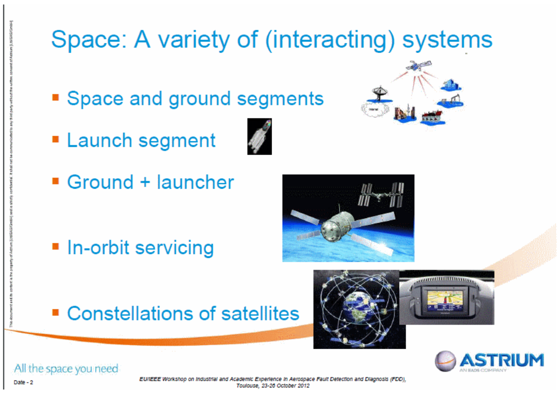
Figure 2-8 EU/IEEE-CSS Workshop on FDD: 2nd day presentations

The last day of the workshop was the turn for the invited Space and Aeronautics agencies to present their activities in the FDIR field and their vision of the direction forward, see Table 4.

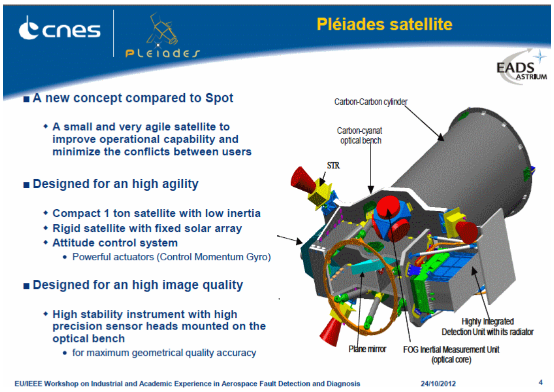
Table 4 EU/IEEE-CSS Workshops on FDD: last day presentations "Agencies & Visions"

Time	Speaker & Organization	Title
09:00-09:25	C.Belcastro (NASA Langley)	NASA Detection, Diagnostics, and Prognostics Research for Aircraft Loss of Control Prevention and Recovery
09:25-09:50	B.Frapard (ASTRIUM)	FDIR in Space – An Astrium perspective
09:50-10:15	P.Viallefont (CNES)	The FDIR concepts on Pleiades optical high-resolution satellite
11:20-12:00	E. Kircher & A.Benoit (ESA)	Technology R&D at ESA and perspective for FDI
12:00-12:25	G.Cuciniello (CIRA)	Analytic Fault Tolerant Navigation for High Lift Re-entry Vehicles
13:25-13:50	J.Bals (DLR)	
13:50-14:15	P.Fabiani (ONERA)	Safe reconfigurable avionic functions in future air systems
14:15-14:40	A.Marcos (Deimos) & P.Goupil (Airbus)	Workshop Conclusion

In terms of the technical presentations we had Benoit Frapard (Director of R&D activities at Astrium) presenting the perspective of Astrium for FDIR and their focus on functional approaches such as model-based, Figure 2-9-[a], Pierre Viallefont from CNES detailing the FDIR of the high-resolution optical satellite Pleaides, Figure 2-9-[b], Giovanni Cuciniello (head of the GNC group at CIRA) showing the development and flight test results for the fault tolerant navigation system of CIRA's Unmanned Space Vehicle (USV), Figure 2-9-[c], Johann Bals (director of DLR's Institute of System Dynamics and Control) summarizing DLR's FDIR activities in the aeronautics and automotive fields, and Patrick Fabiani (director of ONERA's Systems Control and Flight Dynamics group) similarly summarizing ONERA's aerospace FDIR activities, Figure 2-9-[d].

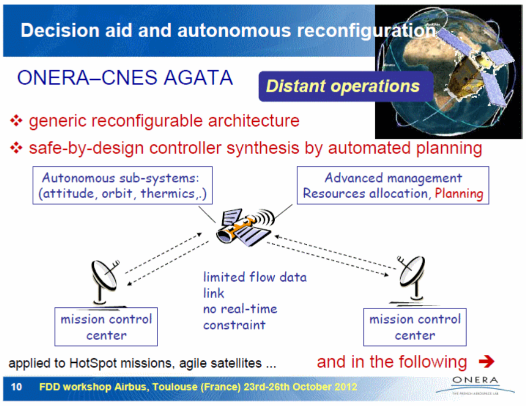


[a] ASTRIUM FDIR



[b] CNRS Pleiades FDIR

[c] CIRA USV fault tolerant navigation



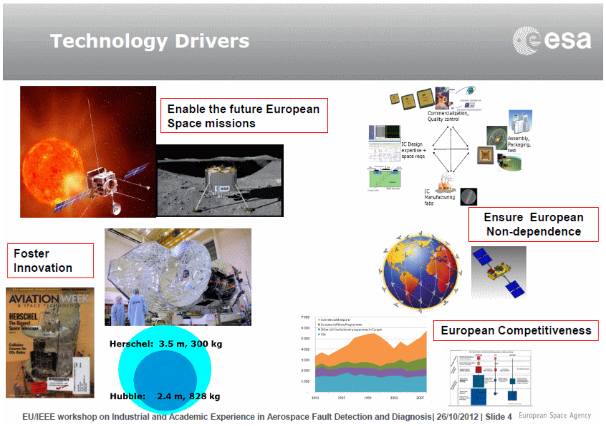
[d] ONERA FDIR activities

Figure 2-9 EU/IEEE-CSS Workshop on FDD: 3rd day presentations

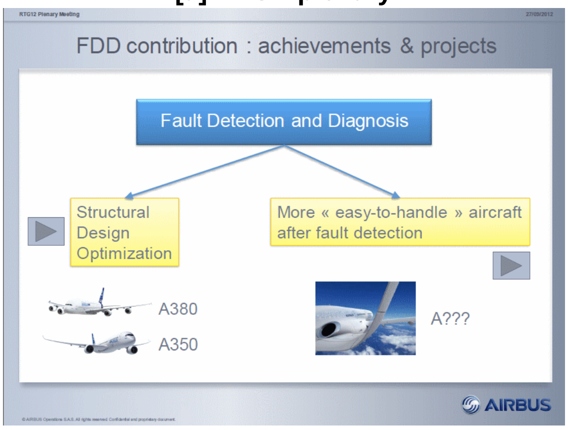
In terms of the plenary talks, we had five high-caliber speakers:

- **Augusto Caramagno**, Head of the Aerospace System Engineering business unit at Deimos Space, presented an overview of Deimos FDIR activities in the Aerospace domain. These included participation in many ESA TRP and programmes related to advanced control and FDIR, flight tests of FDI schemes, and cross-fertilization between FDI/FTC schemes and GNSS technology.
- **Michel Comes**, Vice President and R&T Chief Engineer at Airbus SAS, provided a high-level overview of the R&T advances used nowadays in Airbus and their impact on commercial aircraft programmes.
- **Michael Weiler**, Hydro-Mechanical Systems Expert for Flight Controls, Landing Gear, Hydraulics and Doors at the European Aviation Safety Agency (EASA), focused on the specific regulatory aspects and challenges that FDIR technology faces for implementation in aircraft.
- **Christine Belcastro**, Senior Research Engineer at NASA Langley Research Center, provided a detailed account on NASA Aviation Safety Program in terms of goals, projects, current and future risks, and potential future directions for Diagnostic & Prognostic.
- **Eike Kircher**, Head of Basic TRP & Technology Strategy Division Systems at ESA-ESTEC, presented a joint presentation with Alain Benoit, head of the Control Systems Division. The two focuses of the talk were the technology R&D drivers, elements and processes at ESA-ESTEC and the FDI perspective seen from ESA workshops, standardisation efforts, projects and technology requirements.

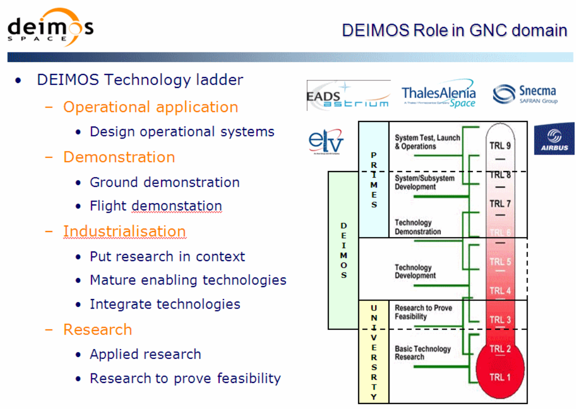
[a] NASA plenary



[b] ESA plenary



[c] AIRBUS plenary



[d] DEIMOS plenary

Figure 2-10 EU/IEEE-CSS Workshop on FDD: plenary presentations

2.3 CONCLUSIONS

The workshop was considered a success by the attendees due to the possibility to attend the demonstration on Airbus V&V facilities of the FDD designs developed in ADDSAFE, the possibility to interact with experts outside the standard conference circuit, the wide array of technical presentations within the FDIR umbrella, and the excellent local organization facilities provided by the Airbus team (thanks to Dr. Philippe Goupil and the rest of the local team).

In terms of conclusions in an Industry versus Academic perspective, the following was noted[1]:

1. Models & Benchmark

- ***Industry perspective***
  - *Proprietary*. The models and benchmarks provided by industry are proprietary and this must be respected and used solely for the established purposes and project.
  - *Limitations*. There will be always limitations on the models, by virtue of the difficulties to adequately model physical phenomena or the need to simplify the released models.

  The above issues arise due to the difficulty to obtain and the need to protect models and benchmarks –which have been developed over many years, with a high level of investment and that are critical to the business of the industrial partner.

- ***Academic perspective***
  - *Proprietary*. In order to show the advantages and limitations of the methods it is necessary to have adequate models and with sufficient detail.
  - *Limitations*. It is necessary to have guidance and sufficient information on the limitations of the models/benchmark and real problems from the industrial experts.

  The more details on the benchmark/scenarios/models are provided, the better the job the academic community can do.

Conclusion: There has to be a common undertaking in using and improving the models/benchmarks. Both sides typically agree on their need but often times Industry is over protective or provides limited information to efficiently use the models while Academia typically considers modelling a minor contribution and expects that any issue with the models (even if it arises from the specific approach they use) is the solely responsibility of the Industrial partner.

2. Certification and V&V

- ***Industry perspective***
  - *No certification, no flight!!!* All methods must take into account, or at least address, certification issues if they are to be considered by Industry.
  - *Standards & Experience*. There are many quantified rules (certification standards and regulations) but also imponderable experience from industrial experts guiding many times the selection, design and implementation of a specific technology.

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[1] Any kind of subjective, erroneous or misleading conclusion is the sole responsibility of the author of this report.

In order to adequately transfer any technology to industry it is necessary to provide sufficient understanding of the methods so that the above two issues can be addressed by the industrial teams. This requires among other things: a step-by-step design methodology, transparent engineering process and (physically-based) tuning rules. Very sophisticated mathematical theories applied to very simplified problems do not serve to assuage industry concerns on the validity of the method.

- ***Academic perspective***

    - *Industrial collaboration is key!!!* The role of the academic partner is not to become an expert on certification issues thus industry must accept that a close collaboration is necessary to provide adequate guidance.

    - *Standards and Experience*. It is necessary to have well defined constrains from industry but these must be clearly stated and streamlined (i.e. saturation with the full set of regulatory requirements must be avoided).

    Incremental verification of the methods is most desirable for Academia to demonstrate the potential advantages and disadvantages of the methods. In order to do this, simplified models/benchmarks representing specific issues critical for the industrial partner should be provided in addition to a more sophisticated version for internal validation. Clear metrics and or rules of thumb reflecting the most critical certification issues and experience are key to provide a clear methodology and tuning-rules.

In summary, the conclusion of the workshop was that the success of an academic/industry project attempting to achieve a TRL >5 relies on the willingness from industry to provide information, continuous guidance and the use of test facilities otherwise outside the access of academics throughout the entire project while on the academic side it is necessary to respect the limitations (providing positive feedback or directly become involve in improving the models/benchmark), respect the proprietary nature of the models and information, and emphasize the transparency, methodology and physical-tuning of the approaches and designs.

And to conclude, a collection of photos from our (most good-looking) speakers ;) …

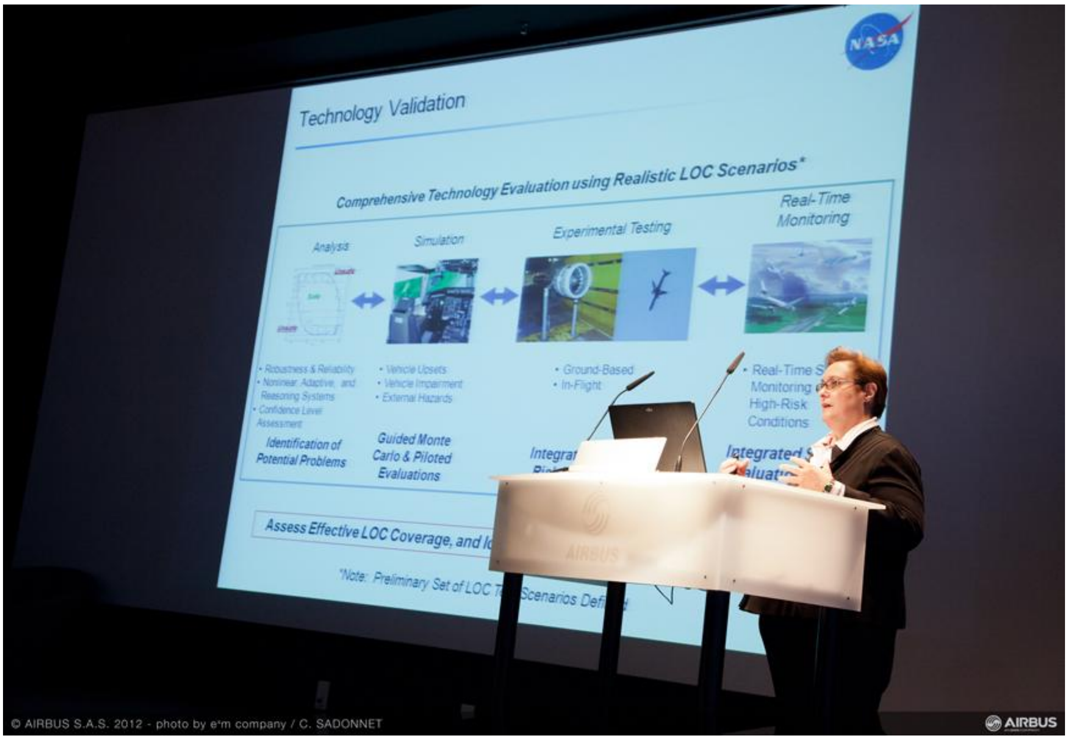

Figure 2-11 EU/IEEE-CSS Workshop on FDD: NASA Langley plenary speaker Dr. Christine Belcastro

Figure 2-12 EU/IEEE-CSS Workshop on FDD: ESA-ESTEC plenary speaker Mr. Eike Kircher

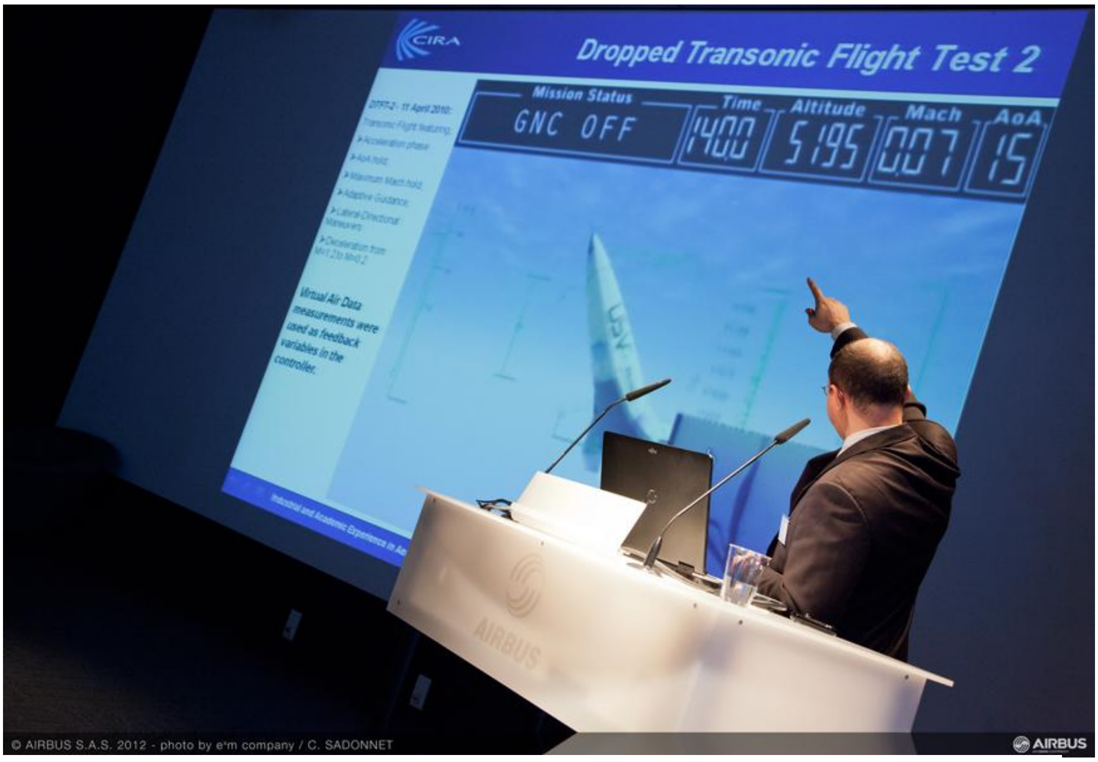

Figure 2-13 EU/IEEE-CSS Workshop on FDD: CIRA speaker Giovanni Cuciniello

Figure 2-14 EU/IEEE-CSS Workshop on FDD: ONERA speaker Dr. Patrick Fabiani

3 EU-FP7 PROJECT "ADDSAFE"

3.1 INTRODUCTION

The state-of-practice for aircraft manufacturers to diagnose guidance & control (G&C) faults and obtain full flight envelope protection at all times is to provide high levels of hardware redundancy in order to perform coherency tests and ensure sufficient available control action. This hardware-redundancy based fault detection and diagnosis (FDD) approach fits also into current aircraft certification processes while ensuring the highest level of safety standards. However, these FDD solutions increase the aircraft weight and complexity and thus its manufacturing and maintenance costs. Moreover, its applicability is becoming increasingly problematic when used in conjunction with the many innovative solutions being developed by the aeronautical sector towards achieving the future "sustainable" (More Affordable, Safer, Cleaner and Quieter) aircraft.

This applicability gap has resulted in a de facto "fault diagnosis bottleneck", a technological barrier constraining the full realization of the next generation of air transport due to the need to ensure the current highest levels of aircraft safety when implementing novel green and efficient technologies.

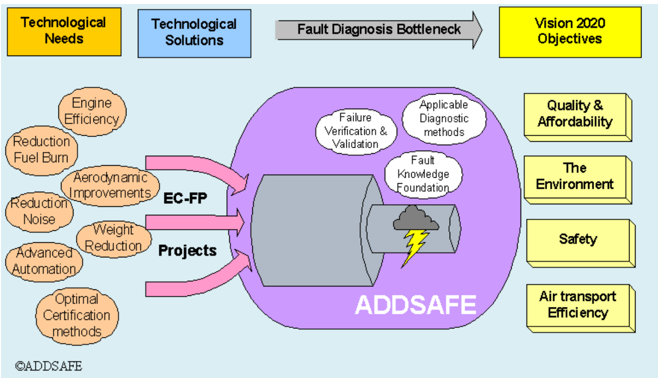

Figure 3-1 ADDSAFE: Fault diagnosis bottleneck concept

In order to address the above issues a consortium of European industries (Airbus, Deimos Space), research centers (DLR, SZTAKI, IMS-CNRS) and Universities (Delft, Leicester, Hull) was established with funding from the EU 7th Framework Program. The project, led by Deimos Space, was entitled "**Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE)**". The project web page is: http://addsafe.deimos-space.com/.

Figure 3-2 ADDSAFE Consortium geographical distribution

The Kick-off of the project was on July 2009 at Deimos Space premises in Madrid and concluded with a Final Meeting and International Workshop on October 2012 at Airbus facilities in Toulouse.

Figure 3-3 Kick-Off meeting (Madrid, July 2009)

Figure 3-4Final Meeting (Toulouse, October 2012)

The **overall aim of ADDSAFE** was to research and develop model-based FDD methods for aircraft flight control systems faults, predominantly sensor and actuator malfunctions. Highlighting the link between aircraft sustainability and FDD, it can be demonstrated for example that improving the fault diagnosis performance in flight control systems allows to optimize the aircraft structural design (resulting in weight saving), which in turn helps improve aircraft performance and to decrease its environmental footprint. The results are expected to help achieve the European Vision 2020 challenges related to the “greening” of the aircraft (by supporting the application of already developed sustainable solutions) and of “safety” (by opening the door to the use of new technologies while maintaining the current aircraft safety levels).

From a technological and scientific perspective the main benefits of the project are:

1. Identification of a set of guidelines for FDD design and analysis for aircraft G&C
2. Improved FDD methods and understanding of their applicability to aircraft FDD
3. A step towards a V&V process for advanced aircraft diagnostic systems
4. Demonstration of the most promising model-based FDD designs on industrial state-of-art flight simulation platforms.

From the perspective of the benefits to society, ADDSAFE strived to:

1. Support greener technical solutions
2. Maintain current highest safety standards
3. Improve aircraft transport cost & efficiency

The work-break-down (WBS) structure of ADDSAFE followed a three-year period and was divided into 6 main work-packages decomposed into a total of 14 technical work packages. The project strived to combine the synergies between the scientific and the technological (i.e. industrial) partners at all levels of the FDD development cycle.

3.2 SUMMARY OF RESULTS

The project was divided into two main phases. For the 1st phase of the project, between Kick-off (M0) and Critical Review Meeting (M19), the focus of activities was on two main development lines while for the 2nd phase it was dedicated to the last two:

(i) Developing the FDD benchmark and associated V&V tools.

(ii) Researching the FDD methods.

(iii) Demonstrating the applicability of the FDD methods.

(iv) Benchmarking, verifying and validating the resulting FDD designs.

1. **FDD Benchmark and associated V&V tools**

The benchmark definition included a description of the fault scenarios and of the aircraft model development.

Three kinds of scenarios were defined covering a wide range of possible sensor and actuator faults related to structural design objectives and aircraft performance. For all scenarios, required probabilities of false alarm as well as missed detection were specified based on real industrial constraints. The project was defined in order to have a strong practical component so as to transfer to the industrial world the selected methods. For example, among other criteria, a high level of systematic FDD design tuning is typically required in industry so the proposed solutions had to be assessed for possible use on different control surfaces and different aircraft. Thus, in the fault scenario description, the acceptable tuning complexity from an industrial point of view was defined.

The aircraft model used as part of the FDD benchmark was highly representative of a generic twin-engine civil commercial aircraft. It included a nonlinear rigid-body aircraft model with a full set of control surfaces, actuator models, sensor models, flight control laws (FCL) and pilot inputs. It was a closed-loop, non-linear model based on the representation depicted in Figure 3-5and allowed exploring the whole flight domain considering a wide class of pilot inputs and wind perturbations.

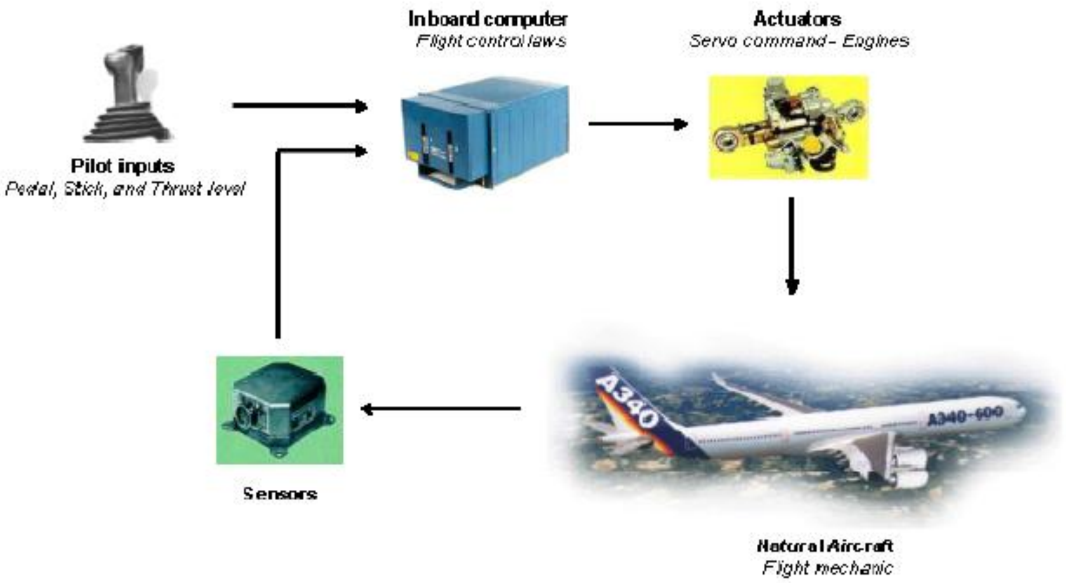

Figure 3-5 Airbus closed-loop aircraft model main components

2. Industrial verification and validation (V&V) tools

The importance of the studies carried out within the project arose, on the one hand, due to the industrial representativeness of the benchmark proposed by Airbus and, on the other hand, the industrial validation of the more promising designs in the actual Airbus flight control system Verification & Validation (V&V) process –depicted below.

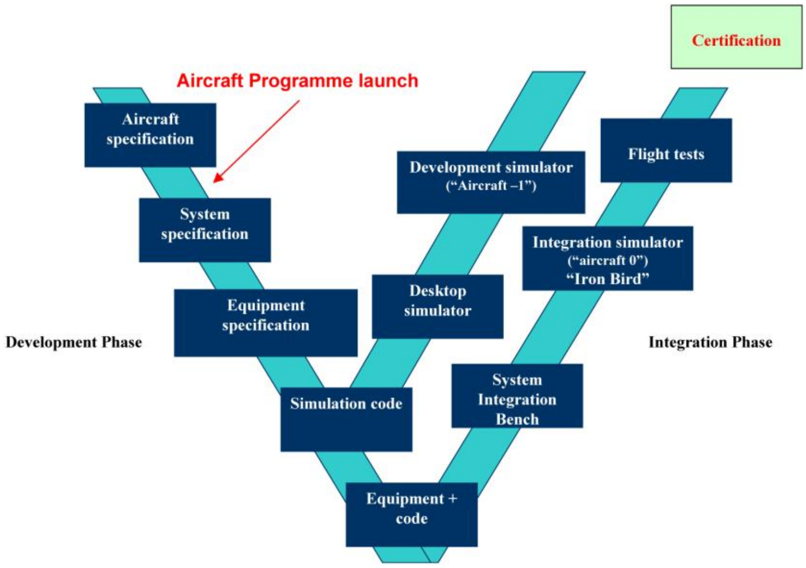

Figure 3-6 Airbus traditional V&V framework

ADDSAFE addressed the development and the integration phases: from FDD design coding to high-fidelity simulators (flight tests were not part of the project). Indeed, a key step for the successful transfer to the aeronautics practitioners of the developed FDD methods was their demonstration on standardized industrial validation processes. The proposed V&V was a two-step process: first, an industrial software assessment tool (FES) was used and secondly, validation on physical aircraft rigs was performed.

FES (functional engineering simulator) is a term used in Space to describe a software simulator describing at a functional level the components of a system including its operating environment. FESs are used in support of the specification, design, verification and operations of space systems, and can be used across the spacecraft development life-cycle, including activities such as system design validation, software V&V, spacecraft unit and sub-system test activities.

From an aircraft manufacturer point of view, all new types of equipment installed in the cockpit and in the aircraft avionics compartment must be tested, including checking their connection to the other aircraft equipments as well as their integration. After a first assessment of the equipment itself (e.g. on a desktop simulator for validating a flight guidance and control function), there are two levels of integration test facilities:

- The System Integration Test Bench (SIB) for validation in an environment restricted to a single, specific aircraft system function (e.g. FCS)
- The integration simulators ("Iron Bird" or flight simulator) for validation in full a/c environment.

For the ADDSAFE project, the choice of the validation test facility depended on the characteristics of the FDD designs and it was also associated to the fault scenario coverage.

3. FDD methods: research and application

Most of the model-based methods rely on the idea of analytical redundancy in which, in contrast to physical or hardware redundancy, real physical measurements are complemented with analytically computed redundant variables. 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 estimate of that output generating a so-called residual. The generated residual has to include enough information to determine that a specific fault has occurred. The basis of the design 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 modelling errors and uncertain disturbance effects acting upon the system being monitored. If the residual signals maintain these sensitivity properties over a suitable range of the system's dynamic operation, then we can say that a robust FDI can be achieved.

Figure 3-7 presents a pictorial representation highlighting the main conceptual differences between hardware and analytical redundancy FDD schemes (as well as between analytical open and closed loop approaches).

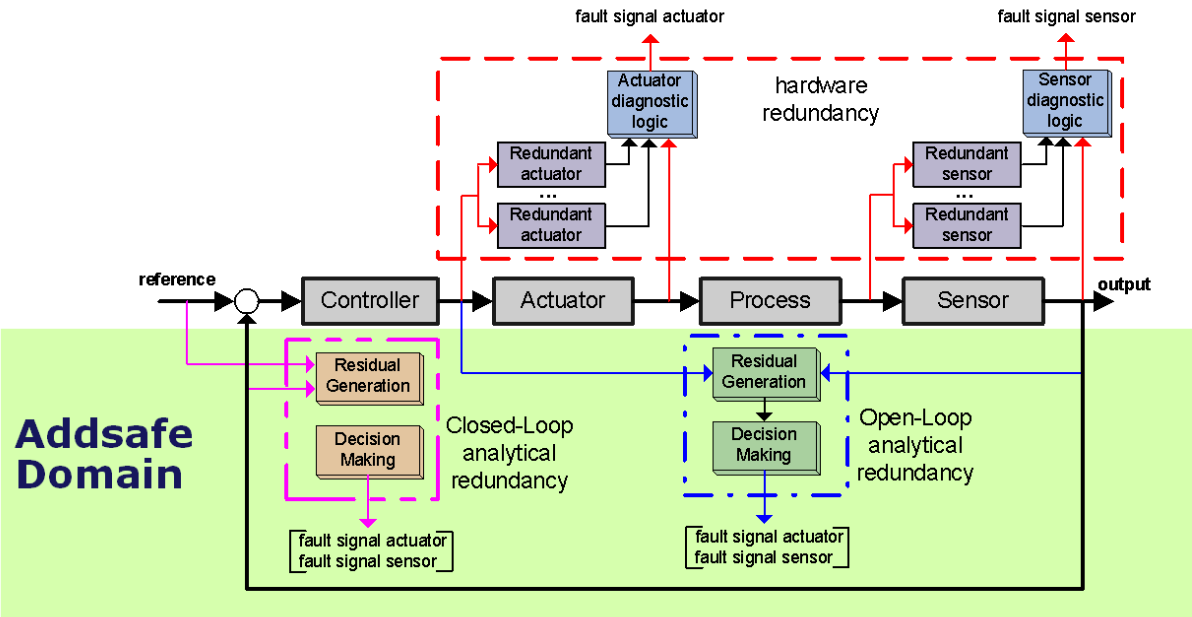

Figure 3-7 ADDSAFE: Hardware vs. Analytical redundancy

The approaches followed in ADDSAFE were divided into two main categories:

1. **Traditional model-based FDD approaches**. These approaches place emphasis on the use of a more or less accurate model of a linear time invariant (LTI) system. In essence, these methods generate residuals from 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.

   These techniques have been shown to work well in a number of real applications but might encounter difficulties when it comes to their use in aerospace applications where the dynamics, perturbations and safety-critical limits encountered are very difficult to handle.

2. **Advanced model-based FDD methodologies.** Methods explicitly dealing with challenging issues of practical applications (e.g. handling of nonlinearities and dynamic variations) together various optimization techniques (allowing fast and optimal FDD system tuning and robust detection) have appeared within the academic community in the past years. These techniques attempt to overcome the shortcomings of traditional FDD approaches both in terms of detection performance and robustness, and as such, they are widely referred to as advanced.

   Advanced FDD approaches represent a logical shift from the traditional linear approaches towards nonlinear and advanced optimization methods. At the same time, these advanced approaches can open up the possibility to reduce the fault detection levels with the direct consequence of improving aircraft performance and its environmental footprint. Nevertheless, the sophistication demanded by these advanced FDD methods has often limited their use in the industrial practice.

4. Benchmarking, verifying and validating the resulting FDD designs

Benchmarking & Verification

An initial assessment of all the preliminary designs was performed using Deimos' benchmarking FES. This preliminary benchmarking guided the subsequent maturation of the FDD designs. The matured designs were then ported by the partners using a special Simulink block-set library developed by AIRBUS based on their SAO/SCADE flight-code-ready generation software. Subsequently, the ported designs were verified and benchmarked by Deimos through application of a Monte Carlo campaign composed of 2200 runs (1200 fault-free and 1000 with specific faults). The first set of cases was used to assess the false alarm (FA) metric (which is the most critical for an actual deployable FDD) while the second looked more specifically to the missed detection (MD) and the detection time performance (DTP) metrics. In order words, the first case looked at robustness and the second to performance of the FDD designs. The FES verification/benchmark results were:

- All the designs but 4 obtained maximum DTP well below the maximum allowed.
- All the designs obtained satisfactory MD% ---one case suffered a 0.3% MD which is considered acceptable.
- All the designs but one had zero FA%.

Initially only <u>two</u> FDD designs were to be selected to continue to the industrial validation process and demo due to the cost of the process. But, thanks to the high capability and potential of the designs (as measured by the quantitative metrics results), as well as the interest of AIRBUS, <u>five</u> designs were pre-selected.

Validation

The validation activity included the very long and strong Airbus' experience on aircraft system industrial validation in general, and specifically the industrial development and validation of Flight Control Computer software. The chosen approach was to involve in the earliest phases of the project all AIRBUS teams typically involved in the industrial validation: Flight Control System specialists and experts, Flight Control Software coding team, and Flight and Integration Tests teams.

The validation work performed implied two main steps: (i) preparation of the experimental set-up for industrial validation, and (ii) industrial validation on Airbus test facilities.

Once the selected FDD designs were implemented inside the FCC, the implementation of the FDD designs was validated during severe simulation campaigns on several kinds of simulators. The validation consisted also of two phases: the detection capability and the robustness assessment. The robustness assessment consists of a series of typical manoeuvres, some of them with a strong control surface dynamic: flight control checks, push-over, take-offs in nominal configurations as well as degraded configurations (engine failure, crosswind...), Auto-Pilot disconnection, slats/flaps configuration changes, side-step, “duck-under”, etc...

It is noted that initially only two V&V campaigns were programmed due to the cost of these (i.e. the may involve up to 20 different engineers). Nevertheless, Airbus felt that it was possible to include one more campaign due to the simultaneous testing of similar FDD designs and furthermore and additional 4th campaign was performed thanks to Airbus internal funds. The latter clearly indicates the interest of Airbus on the developed methods.

The V&V campaign results, as well as the lessons learnt, have shown that the industrial transfer depends on a better understanding of the methods, which are still considered as quite complex by the main industrial partner, but in conclusion, the V&V campaigns are considered as very promising from an industrial point of view.