**Nationaal Lucht- en Ruimtevaartlaboratorium**

National Aerospace Laboratory NLR

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# Simulation of an Affordable Fly-By-Wire System for Small Commercial Aircraft

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ABSTRACT

The Affordable Digital Flight Control System for Small Commercial Aircraft (ADFCS) programme investigated the feasibility of introducing fly-by-wire (FBW) technology to the small and medium commercial aircraft market. An architecture was developed for a cost-effective FBW Digital Flight Control System (DFCS) for small and medium commercial aircraft utilizing new technologies based on Fuzzy Logic, Neural Networks and Robust Control to reduce the overall system costs. The feasibility of the innovative FBW technologies was demonstrated by simulated flight tests. This paper presents an overview of the ADFCS programme and, more specifically, an insight into the simulator evaluation process effectively conducted as part of the project. The main achievement of the project has been to challenge the state-of-the-art technology and prove that new technologies have the potential to improve the affordability of FBW for small and medium commercial aircraft in a safe manner. To further mature the developed system, based on the most promising technologies and identified cost drivers, a follow-up project has been initiated (ADFCS-II). The successful international co-operation within the ADFCS consortium may prove to be a basis for further innovations aimed at increasing the affordability of FBW technology for small to medium commercial aircraft.

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## Summary

The Affordable Digital Flight Control System for Small Commercial Aircraft (ADFCS) programme investigated the feasibility of introducing fly-by-wire (FBW) technology to the small and medium commercial aircraft market. An architecture was developed for a cost-effective FBW Digital Flight Control System (DFCS) for small and medium commercial aircraft utilizing new technologies based on Fuzzy Logic, Neural Networks and Robust Control to reduce the overall system costs. The feasibility of the innovative FBW technologies was demonstrated by simulated flight tests. This paper presents an overview of the ADFCS programme and, more specifically, an insight into the simulator evaluation process effectively conducted as part of the project. The main achievement of the project has been to challenge the state-of-the-art technology and prove that new technologies have the potential to improve the affordability of FBW for small and medium commercial aircraft in a safe manner. To further mature the developed system, based on the most promising technologies and identified cost drivers, a follow-up project has been initiated (ADFCS-II). The successful international co-operation within the ADFCS consortium may prove to be a basis for further innovations aimed at increasing the affordability of FBW technology for small to medium commercial aircraft.

## Contents



(24 pages in total)

## Abbreviations

| | |
|---|---|
| ADFCS | Affordable Digital Flight Control System |
| AOA | Angle of Attack |
| CVS | Common Vector Space |
| FBW | Fly By Wire |
| FCL | Flight Control Law |
| FCS | Flight Control System |
| FDI | Fault Detection and Identification |
| LOES | Low Order Equivalent System |
| MOSAIC | Model-Oriented Software Automatic Interface Converter |
| RTS | Real Time Software |

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# 1 Introduction

In current large transport aircraft, FBW technology provides advantages in the field of flight safety, direct operating costs and aircraft handling. Extension of these benefits to small or medium commercial aircraft is very desirable but will only be achieved if the cost of the technology can be reduced.

FBW technology is state-of-the-art in modern medium to large civil transport aircraft. In small commercial aircraft (business jet/regional), the flight control systems are mechanically signalled and most of them are also hydraulically powered. Currently, several aircraft manufacturers are considering adopting FBW technology for new generation small and medium commercial aircraft. These developments are potentially very significant in the highly competitive small-medium aircraft market.

To compete with conventional control systems on basis of cost effectiveness, new generation FBW systems will be characterised by:

- Minimisation of the number of different parts in the system;
- Use of low cost, full authority, actuation system for both primary control and autoflight, with (as far as possible) identical types of actuation devices;
- Full integration of flight control, autoflight, flight management and actuation systems in order to avoid costly duplication of functionality and expensive interfaces;
- Application of advanced / automated methods for control law design, based on specified design requirements and handling qualities criteria;
- Low cost sensor systems;
- Extremely high integrity and improved dispatch capability, using advanced methods for failure detection, failure isolation and system reconfiguration;
- Low maintenance cost, by capitalising on the low part number count and applying deferred maintenance principles;
- Omission of any type of mechanical backup systems.

# 2 ADFCS project

The ADFCS project was initiated in 1998 to study the feasibility of developing an affordable FBW digital flight control system (DFCS) for small to medium size commercial aircraft (30,000-60,000 lb. max. takeoff weight). The goal of the project was to develop and evaluate an architecture for an affordable FBW-DFCS for small and medium commercial aircraft, utilising advanced technologies such as Robust Control, Neural Networks and Fuzzy Logic algorithms, aimed to reduce the system development cost and the operational cost of the aircraft. The project, which lasted three years and was performed within the European Fourth Framework Programme, was carried out by seven partners from four different countries (*table 1*). The definition of a FBW-DFCS for small commercial aircraft would provide preferred automatic control solutions, including design recommendations for development and incorporation of the flight control system into a new airplane design. The project would provide the European aircraft manufacturers and avionics suppliers with the capability to apply digital FBW technology to small and medium civil business and transport aircraft in an affordable manner.

FBW technology applications based on Classical Design Techniques, Robust Control Law Design Techniques, Fuzzy Logic and Neural Networks, in combination with automated design processes, were identified and evaluated. The main objective was to investigate the possibility to improve the control law design process and redundancy management in the system by replacing physical sensors (recurring cost items) with complex software algorithms (analytical redundancy representing non-recurring development costs) and thereby obtain enhanced affordability compared to the common conventional (mainly mechanical) systems currently implemented in small aircraft. The developed FBW system designs were prepared for pilot-in-the-loop simulations to evaluate the advanced technologies according to realistic flight test requirements. The evaluation was performed on a motion base research simulator, configured as rapid prototyping environment, by an experienced flight test team. The main goals of the evaluation programme were to test the feasibility of the developed FBW flight control concepts in the areas of flight safety, controllability, handling qualities, redundancy management and ability for self reconfiguration after predefined system failures.

Table 1: ADFCS project partners

| | |
|---|---|
| IAI | Israel Aircraft Industries (Israel) |
| ALN | Alenia Aerospazio (Italy) |
| NLR | National Aerospace Laboratory (The Netherlands) |
| CIRA | Centro Italiano Ricerche Aerospaziali (Italy) |
| DUT | Delft University of Technology (The Netherlands) |
| Technion | Israel Institute of Technology (Israel) |
| BAE | BAE SYSTEMS (United Kingdom) |

### 2.1 FBW System Development

A baseline DFCS was designed using current classical design techniques comprising a conventional set of control laws, envelope protection modes and fault detection and identification (FDI) functionality. The architecture (*figure 1*) was designed to provide flexibility for the substitution of new technology FBW subsystems (i.e. conventional FDI block should be simply replaceable by one of the developed alternatives). A duo-triplex architecture was proposed as representative of state-of-the-art technology for small commercial aircraft.

A cost-of-ownership model was developed to assess the feasibility of bringing the benefits of FBW technology to the small commercial aircraft market. The model enabled the identification of major cost drivers that could best benefit from the application of new technologies.

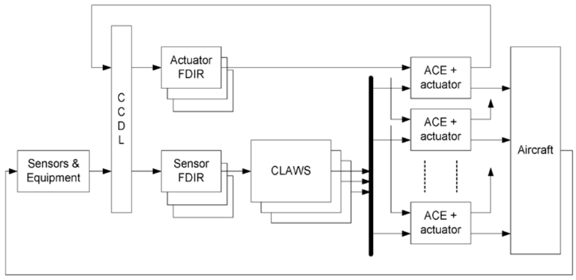


*Figure 1: ADFCS top level FCS architecture*

### 2.2 New Technology FBW Applications

The project identified areas in FBW technology that seemed promising for the application of innovative technologies based on Fuzzy Logic, Neural Networks and Robust Control.

Fuzzy Logic is an extension of Boolean conventional logic (*true/false*) to manage the concept of partial truth (truth values between "*completely true*" and "*completely false*"). The control strategy of a Fuzzy Logic controller is implemented in the form of *if-then* rules in the rule base. The rules represent an approximate static mapping from inputs to outputs. An extensive analysis was performed in order to identify the most promising topics. In the field of control laws, Stability Augmentation, Envelope Protection and Pilot Command Shaping were tagged as most promising.

To improve the efficiency of the control law design, *Fuzzy Gain Scheduling* was investigated[1]. This provides automated procedures for gain-scheduled design based on fuzzy clustering and fuzzy logic control. Major savings achieved are through a significant reduction in design areas to cover the flight envelope and continuous gain scheduling being obtained by means of fuzzy interpolation. The concept shows good potential for automated design and performed similarly to a classical control system in the simulator.

*Envelope protection* based on Fuzzy Logic technology was evaluated to reduce design and tuning time, complexity of the control law architecture and increase robustness. The method was developed for angle of attack and bank angle protection and proved to be promising and to out-perform the conventional envelope protection system.

To automate the control law design process further, a *Robust Control* design procedure, based on the *Mu-Analysis and Synthesis theory* was developed and its results demonstrated in the simulator[2]. Apart from reduction in the design effort, the method proved to be successful during the piloted simulator evaluation.

The project identified specific applications concerning redundancy management and FDI, using innovative approaches based on Neural Networks and Fuzzy Logic. In addition, the data and knowledge needed for the FDI applications to be developed by using innovative technologies were analysed. Main identified FDI areas that were further studied and developed were the following:

- Improvement of the conventional voting/monitoring process by adopting Fuzzy Logic concepts.
- Reduction of the level of replication by adopting innovative analytical redundancy approaches.
- Development of innovative FDI related applications based on Neural Networks.

For this phase of the project, redundancy management was restricted to the consolidation and fault detection and identification with respect to sensor signals. The design target was not just to improve the operation, since this is already acceptable to the certification authorities, but to allow fault detection based on a single sensor. FDI technology falls into two classes: self-monitoring and comparison monitoring. Sensor self-monitoring has been extended to the analysis of the signal characteristics by Wavelet analysis[3]. This has been used to characterise the signal attributes and certain characteristics have been associated with fault-induced behavior. The performance of this approach has shown full success for distinctive (abrupt) type of failures. It has also allowed reducing the threshold values in the failure monitors that proved to be a significant problem when desiring an acceptable balance between true fault detection and nuisance indication.

Conventional sensor comparison monitoring allows detection and identification of a fault occurring on one of three signals. With two signals available, only the possibility to detect a difference exists without identifying the faulty one. The ADFCS project investigated several possibilities to extend this performance to provide a full FDI capability with only two sensor signals available. These technologies can be grouped under three classifications - synthetic signal generation, multiple sensor management and virtual sensor technology.

The *synthetic signal generation* class uses a synthetic low fidelity estimation of the signal to monitor and arbitrate between real sensor values when no other means of discrimination exists[4]. This technique has proven to be successful in identifying faults in the case of two significantly different signals. As the accuracy of the synthetic signals is not very good, it is not suited for continuous self-monitoring of a single signal.

The *multiple sensor management* technique groups the several related (like-sensitive) signals into a set. The individual sensor signals are transformed to a Common Vector Space (CVS) where the health and status is assessed. The results obtained with this technique showed that the method is valid and able to identify faults down to the last sensor of a type. However, sensitivity to low drift rate faults could be improved. An alternative signal consolidation method has also been investigated where the FDI generates a confidence factor (membership function) to generate variable weightings for each of the available signals. This may provide smaller failure induced transients.

The *virtual sensor technology* is a true innovation within the project as it provides a high fidelity alternative to a physical sensor with the goal of achieving signal quality sufficient for control purposes[5]. The benefit of this technology is the possibility to continue operation following loss of all true measurement sensors for a limited time. The current issue is that the accuracy of the virtual sensor cannot be assured to detect a failure of the remaining physical sensor in all cases. However, the use of Neural Network technology in this application was successfully demonstrated on the simulator and has shown sufficient potential for further development.

## 3 Simulator evaluation programme

The new technology FBW system designs were prepared for pilot-in-the-loop simulations. The simulator evaluation programme, comprising about 45 test flights (approximately 70 flight hours), was conducted at the National Aerospace Laboratory NLR in the Netherlands using its research flight facilities. The main goals of the evaluation programme were:

- To obtain results on the criticality of degraded mode flying qualities and identification of unknown and unsafe conditions that were not accounted for during the design process.
- To obtain results on aircraft performance and system robustness in off-design conditions.
- Demonstration of the developed redundancy management and reconfiguration strategies using pilot-in-the-loop simulation.

Main emphasis during the simulator evaluation was on the newly designed FBW control concepts including redundancy management and reconfiguration strategies.

The project consortium established a Flight Simulation Co-ordination Team (FSCT). This team was initially tasked with the co-ordination of the extensive simulator preparation work by means of special working sessions/meetings. The objectives for the establishment of the FSCT were:

- To have a smooth and efficient integration in the simulator of the work done in the separate workpackages.
- To co-ordinate the work for the tasks related to simulator preparations, test scenario development and simulator evaluation.
- To have the members of the FSCT, involved in the simulator preparations, assist with their work experience.

### 3.1 FBW Design and Experimental Environment

The developed design and experimental environment (figure 2) presented a flexible common basis for the engineers involved in the design, numerical verification and flight test evaluation of the FBW DFCS. The modular structure and defined interfaces allowed the designers to easily include the developed new technology applications. The environment comprises the complete aircraft and flight control system architecture with a graphical user interface and tools for trimming, linearisation and analysis. Further automation in the design process and performance assessment of the FBW system was achieved by a developed handling qualities evaluation toolbox. This tool was made up of a set of functions that enabled analysis of the aircraft performance against the design requirements. To obtain the data in the proper format for the analysis, functions were included to compute the Low Order Equivalent System (LOES) for both Longitudinal and Lateral-Directional mode. Design parameters were established based on a preliminary set of military specifications tailored for small commercial aircraft applications. All tools were designed within the MATLAB/Simulink™ environment, enabling exchange of design data for rapid system analysis.

### 3.2 Rapid Prototyping

Rapid prototyping in the simulator environment was performed by definition of a standard interface between the development environment and the Real Time System (RTS). An Automatic Software Converter was developed to implement the FBW modules in the simulator environment. This process was based on guidelines for software development in the MATLAB/Simulink™ environment to assure compatibility with that of the simulator. Flight visualisation and analysis tools proved to be an effective reference for analysis of flight test maneuvers and overall FBW system operation.

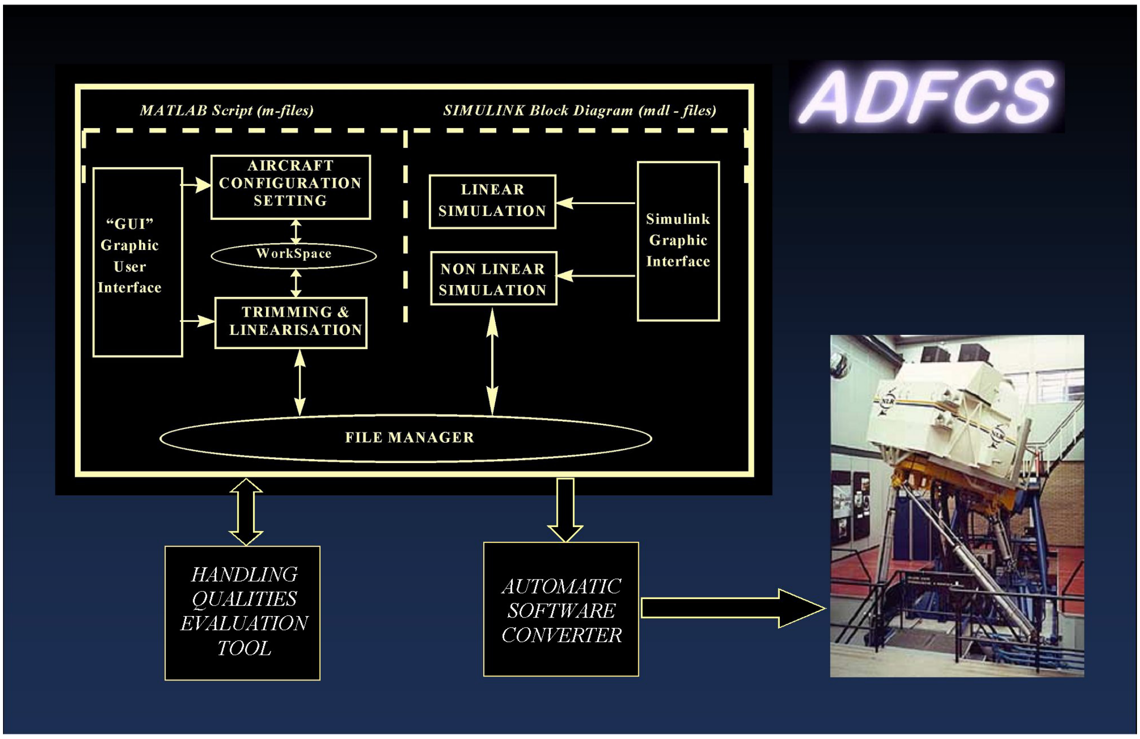


*Figure 2: ADFCS design and experimental environment*

The software environment of the project's research flight simulator is controlled by the Programme and Real-time Operations SIMulation support tool (PROSIM). PROSIM is a generic simulation tool that can be used for design, evaluation and test of a wide range of simulation applications. As it is specially designed for pilot-in-the-loop simulations, it has a great emphasis on accurate real-time control. PROSIM consists of two distinct but related parts:

- The Simulation Development Software (SDS), a generic software environment used to develop and test simulation models and prepare data files that are used during real-time simulation.
- The Real Time simulator Software (RTS), a generic software environment for execution and control of real-time simulations.

Configuring the simulator for rapid prototyping of the FBW designs was performed by the software tool MOSAIC (Model-Oriented Software Automatic Interface Converter) developed during the project (*figure 3*). In essence, MOSAIC has the following capabilities for real-time applications:

- Providing a software shell for multi-model implementation in the RTS environment.
- Preparation of external models for the RTS environment.

The MOSAIC tool performs automated model transfer from MATLAB/Simulink™ to RTS PROSIM. The tool takes as input model source code that has been generated by the Real-Time Workshop (RTW) of Simulink™ and delivers as output model source code that can run in PROSIM, as well as additional PROSIM specific files. Model source code from the FBW designs was provided by each of the design teams based on the guidelines for external software development in the MATLAB/Simulink™ environment.

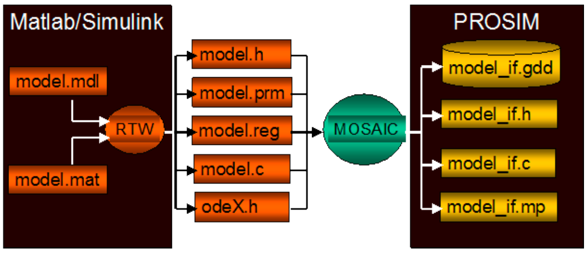


*Figure 3: ADFCS FBW rapid prototyping interface*

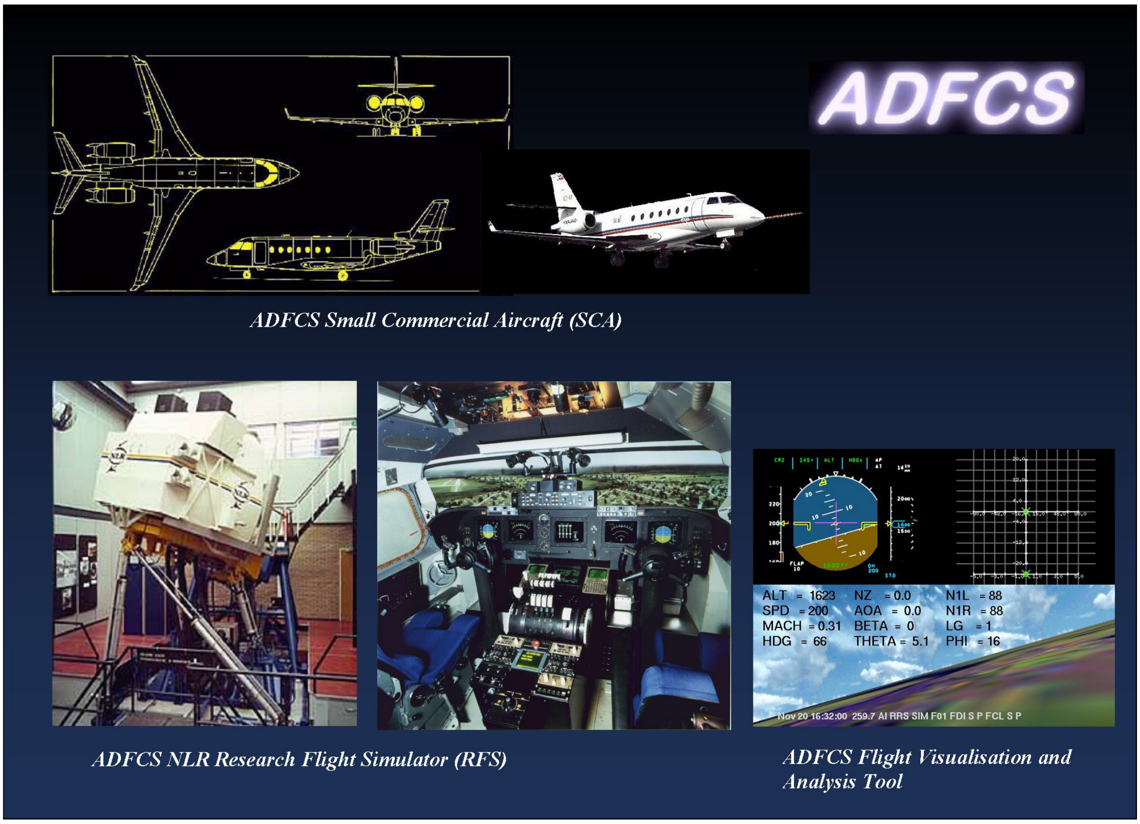


*Figure 4: ADFCS simulator configuration overview*

### 3.3 Simulator Configuration

The ADFCS project utilised the NLR research flight facility in ‘airline’ configuration on a 4 degrees-of-freedom motion platform. Measurement and recording facilities were made available for flight analysis according to ADFCS requirements (figure 4).

The simulator used in the project distinguishes itself from training simulators by its great flexibility to adapt it for all kinds of research projects. For this purpose, the design strategy applied is a high level of modularity, with interchangeable hardware as well as software components. Most components have several options to be operated (i.e. programmable control forces). Furthermore, all aircraft systems are modelled by a software counterpart that enables to modify the functionality of particular systems for research purposes.

The flight deck environment for the simulator evaluation programme was based on the Fokker 100 ‘airliner’ configuration (figure 5). As the evaluation included system assessment in degraded modes, provisions to the Engine Indicating and Crew Alerting System (EICAS) display were made for status monitoring of the FBW system (figure 6). A caution and warning message protocol was defined that included failure status information and flight envelope protection announcements. FBW system status monitoring was integrated on the EICAS display. In addition, the display was configured for in-flight monitoring of angle of attack and load factor.

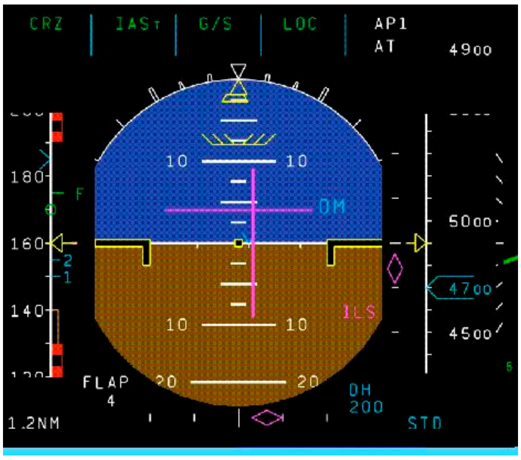


*Figure 5: ADFCS primary flight display (Fokker 100)*

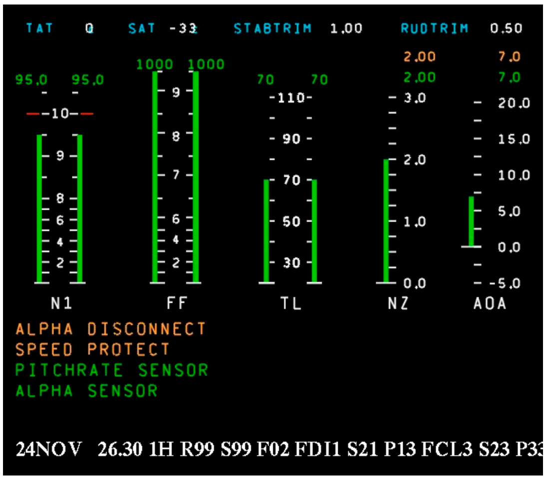


*Figure 6: ADFCS EICAS display including FBW system status monitoring (Fokker 100)*

The simulator environment was configured with online and offline analysis capabilities according to ADFCS requirements (*figure 7*).

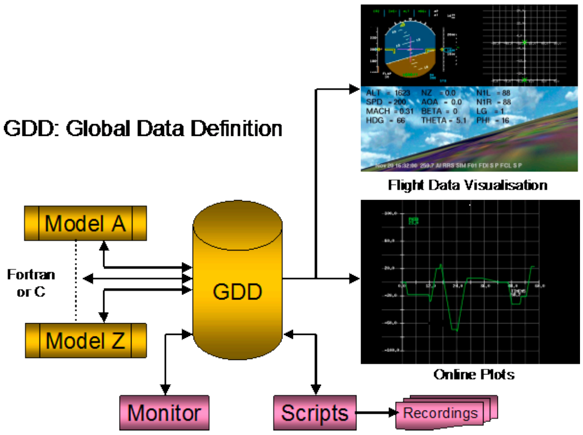


*Figure 7: ADFCS flight data analysis capabilities*

In addition to recorded data, flight visualisation (*figure 8*) was provided for analysis during and after each flight. This data was stored on video for playback purposes and consisted of primary flight data, cockpit control positions, out-the-window view and audible pilot comments during flight. Additional flight parameters were added to record FBW system status data. The flight visualisation tool and playback capability proved to be very effective as a reference for analysis during the evaluation. In addition, the pilots provided written debrief notes. All flight test data, generated during the evaluation phase, was stored on CD-ROM for further offline analysis.

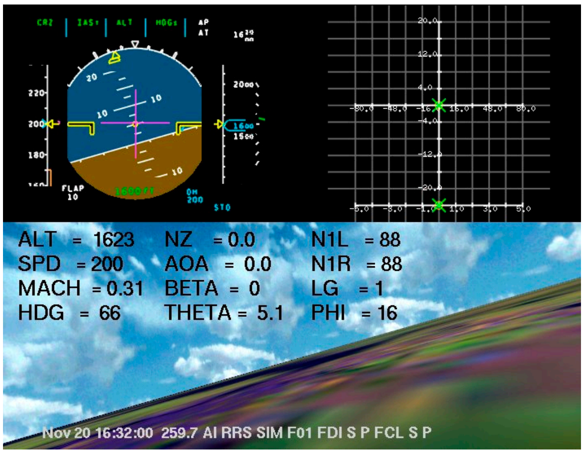


*Figure 8: ADFCS flight visualisation and analysis tool*

### 3.4 Simulator Evaluation

Actual simulator tests (*figure 9*) were approached as a realistic flight-test evaluation conducted by an experienced team of flight test engineers, flight test pilots and certification pilots.

The flight test plan, based on the evaluation test matrix (*table 2*), was prepared for the overall scenario development taking some of the certification requirements into account. The test plan was used as a guideline for the pilot briefing guide written by the flight test engineer (*figure 10*). Failure scenarios were defined covering both mechanical and electrical sensor failures to assess safety, controllability, handling qualities and ability for system self-reconfiguration partly based on certification requirements. To this end, the RTS environment provides a feature for scenario control of the simulation through the ‘Mission Tool’. This tool enables automatic or manual activation of predefined scripts written in the Mission Definition Language (MDL) to inject a specific failure into the system.

*Figure 9: ADFCS simulator evaluation*

Table 2: ADFCS FBW evaluation test matrix

| | | Flight Control System | | | |
|---|---|---|---|---|---|
| | | Classic CLAWS<br>+ Classic Gain Schedules<br>+ Classic Envelope Protection | Classic CLAWS<br>+ Fuzzy Gain Schedules<br>+ Classic Envelope Protection | Classic CLAWS<br>+ Classic Gain Schedules<br>+ Fuzzy Envelope Protection | Robust CLAWS<br>+ Classic Envelope Protection |
| **FDI** | Classic Voter/Monitor | FCL0+FDI1 | FCL1+FDI1 | FCL3+FDI1 | FCL4+FDI1 |
| | Fuzzy Logic (DUT) | FCL0+FDI2 | | | |
| | Fuzzy Logic (DUT/IAI) | FCL0+FDI3 | | | |
| | Neural Net (Technion) | FCL0+FDI4/6 | | | |
| | Fuzzy Logic (BAE SYSTEMS) | FCL0+FDI5 | | | |
| | Neural Net Virtual Sensor (Alenia) | FCL0+FDI7/8 | | | |

The classical FDI method together with the classical control laws were used as a reference for the advanced technologies (fuzzy logic/neural network applications). The part of the test matrix left open did not contribute to the goals of project (*table 2*). It was furthermore assumed that the analytical efforts during the design process would result into preliminary control laws that would met the handling qualities criteria as defined for the project. Full-scale optimisation for any of the control law designs was not carried out. However, to achieve an acceptable baseline reference, simulator tests of the classical control laws were executed until satisfactory handling qualities were achieved.

Following the simulator test, observations were discussed between the flight crew. Results of the foregoing flight were used to consolidate the main problem areas after which the design teams were enabled to perform modification work to the FBW designs. These activities were performed in close co-ordination with the simulator crew and software engineers through a system of request forms and information sheets (*figure 11*). The daily flight tests were not executed until matching test cases for the simulator software were established.

**ADFCS - NLR /RFS - Simulator Flight Briefing – Flight S2/E29**

Flight No. E29 Date: 31/10/00

| INM | W(Lb) | Xcg[%C] |
|---|---|---|
| 01 | 31850 | 27% |
| 02 | 26000 | 27% |
| | | |

Subject:
1. FCL 4 – Pitch Evaluation
2. FDI 4 – Failure detection
3. FDI 7 – Landing / GA + Gust
4. FCL3 – Envelop Protection (AOA)

**Pilot:** Shavit

**FCL0** V6, P40
**FDI4** V1, P01
**FDI7** V1, P01
**FCL3** V4, P04
**FCL4** V2, P10
**FDI9** V4, P04

| Run | | H/Vc/M | Required Maneuver | FCL / FDI |
|---|---|---|---|---|
| | | | | |
| | | | Status String Check | |
| | | | | |
| | | | VTR – Record | |
| | | | | |
| 1. | N01 | 0/0 | Controls Check | Classic/NeoClassic |
| | | 20/DN | | 0-P40/9-P04 |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| 2. | N02 | 3K/140 | Pitch Evaluation | Robust/NeoClassic |
| | | 40/DN | Trim Check | 4-P10/9-P04 |
| | | | | |
| | | | Singlets | |
| | | | | |
| | | | Push / pull to theta | |
| | | | | |
| | | | Engine steps | |
| | | | | |
| | | | Config. change | |
| | | | | |
| | | | Turn compensation | |
| | | | | |
| | | | Stall | |
| | | | | |
| | | | Level Acceleration | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

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*Figure 10: ADFCS simulator briefing*

**ADFCS Simulink Model Change Report**

| ADFCS Module: | |
|---|---|
| Source Version: | New Version: |
| Author: | Date: |
| Description of changes: | |

| Tunable / Off-line / On-line | Old Parameters | (Changed to) New Parameters |
|---|---|---|
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

*Figure 11: ADFCS FBW design modification report*

# 4 Simulator results

The effectiveness of the research simulator, configured as rapid prototyping environment and comprising a highly modular flexibility, was demonstrated during the project. The simulator proved to be an excellent 'exploration' tool for testing the advanced FBW technologies and evaluating their performances and potential benefits. Simulator results are presented for a representative case concerning the evaluation of the virtual sensor concept (evaluated as FDI 7).

In contrast to offline analysis, the simulator enabled extensive analysis of the virtual sensor concept in continuous flight considering different kinds of failures, flight conditions, aircraft configurations and weather conditions. Figure 12 presents flight test data of the developed concept, evaluated in the simulator with a failure of the no.1 angle of attack sensor signal. At t=45 sec., the no.1 angle of attack signal encounters an abrupt failure up to approximately 10 degrees AOA while the valid no.2 angle of attack signal remains at about 4 degrees AOA (upper figure). In this condition, the virtual sensor is still able to predict accurately the valid AOA thus enabling to distinguish between the valid and failed signal up to two physical sensors remaining. At the current state of development, the time traces prove that excellent performance was achieved in steady state conditions and acceptable performance in dynamic conditions. Some biases were noticed in different aircraft configurations that may be solved when the system further matures.

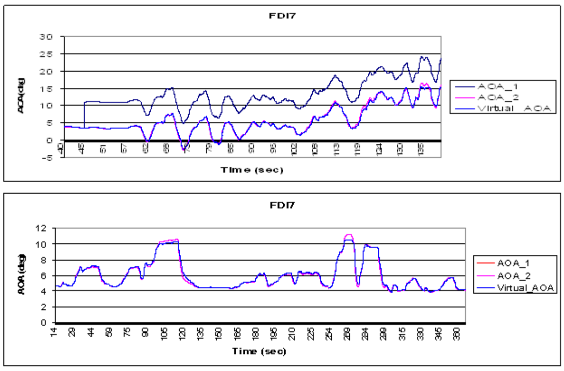


*Figure 12: Virtual sensor performance as obtained in the simulator*

# 5 Summary of main achievements

The main achievements of the ADFCS programme can be summarised as follows:

- Definition, design and demonstration of an affordable FBW system architecture incorporating classical and modern control laws and failure detection techniques. This includes the set-up of the flight control computers, sensor dynamics, redundancy management algorithms, actuator models and system arrangements for failure detection, identification and reconfiguration.

- Thorough evaluation of a complete set of classical FBW control laws on a motion base research flight simulator. This includes the initial refinement of the design flying qualities and envelope protection features for the category of small commercial aircraft considered.
- Identification of the most promising areas for new technology FBW applications in order to further reduce the system development and operational costs.
- Robust control design process and a set of robust control laws demonstrated in approach and landing.
- Proof and demonstration of the Fuzzy Gain Scheduling concept, contributing to reducing the classical control law design effort.
- Proof and demonstration of the Fuzzy Envelope Protection algorithms concept, contributing to system safety and reduction of the design effort.
- Developed multiple failure detection and identification technologies, based on Fuzzy Logic and Neural Networks, demonstrated pilot-in-the-loop.
- Developed virtual sensor concept, based on Neural Network technology trained to reproduce the aircraft angle of attack, successfully demonstrated pilot-in-the-loop.
- Developed comprehensive and comparative cost-of-ownership model reflecting the various costs of a FBW system development, purchase and maintenance as compared to the mechanical system counterpart. For aircraft at or above the mid-weight configuration (50,000 lb.), the initial cost/benefit analysis shows that FBW can be made affordable compared to a conventional mechanical system whilst providing the additional benefits of improved handling qualities and safety features.
- Comprehensive FBW design and experimental environment including nonlinear simulation tools, linear analysis, flying qualities evaluation capabilities and interface definition for rapid prototyping in the simulator environment.
- Developed rapid prototyping environment that dramatically improved the efficiency of the real-time integration process between the simulator facility and developed software. This rapid turnaround system proved to require a carefully defined preparation phase, tight flight-test management and good configuration control.

## 6 Conclusions & future developments

The ADFCS project, performed within the European Fourth Framework Programme, has proven to be an ambitious attempt to investigate new technologies for FBW applications. Its major technical achievement has been to challenge the state-of-the-art technology and prove that new technologies have the potential to improve the affordability of FBW for small and medium commercial aircraft[6].

For the development of new generation affordable FBW systems for small to medium commercial aircraft, flight test programs and flight test management will remain to contribute to the non-recurrent costs related to the design process. The ADFCS evaluation programme, as presented in this paper, demonstrated the effectiveness of the use of simulation facilities for system performance analysis that otherwise cannot be achieved by offline analysis only. Therefore, the use of simulation facilities, especially for advanced FBW technology applications, remains essential. The experiences obtained during the evaluation programme, applied tools and working methods may therefore be used as a 'lessons learned' for further reduction of the non-recurrent costs associated with the design of new technology FBW systems.

A second phase of the project (ADFCS-II) has been initiated within the European Fifth Framework Programme to further mature the most promising technologies. In addition, aspects identified during the project that were outside the scope of the first programme will be addressed.

The successful and effective international co-operation within the ADFCS consortium may provide a good basis for future developments in order to proliferate the benefits of FBW technology to the small and medium commercial aircraft market.

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# 8 References

1. Oosterom, M., Schram, G., Babuška, R., Verbruggen, H.B., *Automated Procedure for Gain Scheduled Flight Control Law Design, AIAA-2000-4253,* Guidance, Navigation and Control Conference, Denver, Colorado, 2000.
2. *Evaluation of Benefits from Modern Control Techniques for a Small Commercial Aircraft FCL Design*, CIRA-CR-SIV-00-126, Centro Italiano Ricerche Aerospaziali CIRA, November 2000.
3. Golan, O.M., Idan, M., Meir, R.,*Weak Model Based Approach for Fault Detection and Isolation of Sensors in Flight Control Systems,* AIAA-2000-4040, Denver, Colorado, 2000.
4. Oosterom M., *Soft Sensor Management and Flight Control Law Reconfiguration*, AIAA-2001-4358, Guidance, Navigation and Control Conference, Montreal, Canada, 2001.
5. Latorre, C., Tranchero, B., *Neural Net-Based Virtual Sensors in Flight Control Systems,* 15$^{th}$ IFAC Symposium on Automatic Control in Aerospace, Bologna, Italy, 2001.
6. *ADFCS Conclusions and Recommendations,* TR-ENG000/001606, Israel Aircraft Industries, Israel, December 2000.