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A Full-Authority Automatic Flight Control System for the Civil Airborne Utility Aircraft S15 – LAPAZ

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Abstract. The market for airborne reconnaissance, surveillance, exploration, and measurement tasks is growing and light civil utility aircraft are suited to fulfil this demand. Missions that are dangerous or extremely long require an automatic flight control system (AFCS) that supports or even replaces the pilot. Such an AFCS for unmanned aircraft operations has to have full authority, it has to be highly reliable, it must be able to follow precisely predefined trajectories, and it must be able to take off and land automatically. The development and certification of such an AFCS at competitive cost is a major challenge. This paper gives an overview on the LAPAZ project, in which an AFCS is developed for the STEMME S15 utility aircraft. It describes the design objectives, the selected flight control architecture, the system as well as the flight test equipment and important flight test results.

1 Introduction

The market for airborne reconnaissance, surveillance, exploration, and measurement tasks is growing. Light civil utility aircraft that can carry the required payloads and that are certified for commercial operations according to EASA CS 23 [1] are suited to fulfil this demand. A motor glider with about 1 ton takeoff weight and payload of 100-300 kg represents a cost-effective and efficient solution. In missions where the pilot or the crew has the task to fly the aircraft while simultaneously operating the payload, an Automatic Flight Control System (AFCS) could significantly support the pilot or may be compulsory. During missions that are dangerous or extremely long, the AFCS can even replace the pilot. As such an

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AFCS has to have full authority it has to be highly reliable. The AFCS shall enable the aircraft to follow predefined trajectories with high precision, to stabilize the aircraft and the measurement systems during measurement flights in turbulent atmosphere, as well as to take off and to land automatically. The development and certification of such an AFCS at competitive cost[2] is a major challenge. This challenge is addressed by the LAPAZ technology project[3], in which an AFCS is developed for a single engine, high-performance motor glider, the STEMME S15 utility aircraft, see Fig. 1.

Fig. 1 Utility aircraft STEMME S15

The objective of the LAPAZ project is to develop and demonstrate such a highly reliable, full-authority AFCS for a utility aircraft. It shall support the crew on long missions and missions near to terrain (low level flight) and it shall allow missions that are beyond the capabilities of human pilots. Possible applications include geo-exploration, agriculture monitoring, photogrammetry, disaster monitoring, fire detection, search and rescue, maritime patrol, as well as coastal and border surveillance. A modular and scalable design shall make the AFCS open for further developments and applications. Future AFCS versions shall support to operate the aircraft as an Optionally Piloted Vehicle (OPV) or as an Unmanned Aircraft System (UAS). Its modular architecture allows adapting the AFCS to other small and medium size utility aircraft.

The LAPAZ project has three partners: STEMME AG as the coordinator, University of Stuttgart's Institute of Aircraft Systems (ILS), and TU Berlin's Department of Flight Mechanics, Flight Control and Aeroelasticity (FMRA). The work share is based on the partner's individual areas of expertise. STEMME provides the aircraft and is responsible for the aircraft integration of the AFCS as well as the execution of HIL simulations and flight tests. ILS is responsible for the devel-

[2] Competitive cost means that the aircraft with AFCS offers advantages in overall mission performance compared to aircraft without AFCS considering non-recurring cost (e.g. for AFCS development) and recurring cost (for EFCS hardware and manufacturing).

[3] The acronym LAPAZ stands for air utility platform for the General Civil Aviation, in German: *Luft-Arbeits-Plattform für die Allgemeine Zivilluftfahrt*.

opment of fault-tolerant *platform instance*[4] of the flight control system, including all redundancy mechanisms. FMRA develops the flight control laws, the flight mechanical simulation model, the human-machine interface as well as a specially designed development process for later certification of the system. The project is funded by the Federal Ministry of Economics and Technology (BMWi) in the National Aerospace Research Program (LUFO IV) from 2007 until 2013.

This paper gives an overview on the AFCS development for the STEMME S15 utility aircraft that was performed in the LAPAZ project. It describes the design objectives, the selected flight control architecture, the system as well as the flight test equipment and important flight test results.

2 Aircraft

The utility aircraft S15 is a variant of the motor glider S6 that is designed for commercial applications, see Fig. 2. It is certified according to EASA CS-23. It has a wingspan of 18 m and a maximum takeoff mass of about 1.1 tons. Its maximum cruising speed is approximately 270 km/h and stall speed is 90 km/h (flaps in takeoff position). The service ceiling is 25,000 ft and the endurance of 8 hours can be increased by ferry tanks. The S15 propulsion unit consists of a turbocharged four-stroke engine BOMBARDIER ROTAX 914 S, a reduction gear and a constant speed propeller with variable blade position.

Fig. 2 STEMME S6/S15

[4] *Platform instance* arises by specialization of the Flexible Avionics Platform, here for the AFCS of the S15.

The standard aircraft has a mechanical flight control system where the pilot's control devices are linked to control surfaces by rods and cables, see Fig. 3. The pilot commands elevator and aileron deflections with a centre stick. The two outer flaps of the three trailing edge flaps of each wing half are used as ailerons (asymmetric deflections). Symmetric deflections of all trailing edge flaps support take-off and landing and can be used to optimize cruise performance. The pedals command rudder deflections and steer the nose wheel, which is connected to the pedals when the aircraft is on ground. Efficient airbrakes can be used for speed and flight path control. Elevator trim is achieved by a spring that the pilot can move by means of an electrical motor to bring the stick into a force-free position. The engine thrust is commanded by a throttle lever and propeller rotation speed is controlled via the control unit for propeller pitch.

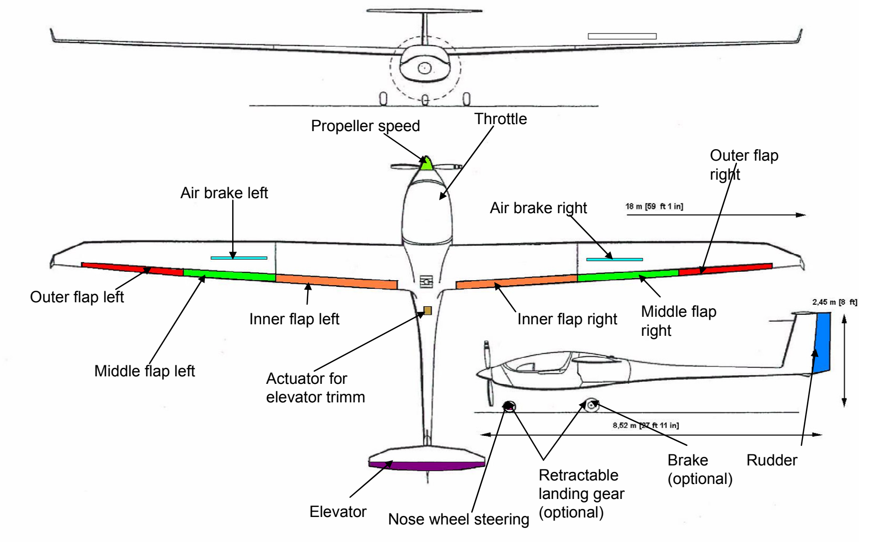

Fig. 3 S15 Flight Control Surfaces

Early in the project it was decided to use the existing and certified linkages of the mechanical flight control system as the basis for the AFCS. The AFCS commands are added mechanically by means of electrical actuators. In case of a failure, the AFCS redundancy management opens the affected clutch or clutches. In this way any failed actuator can be isolated.

If the pilot wants to take control he can decouple the system by means of the fast decoupling device (FaD). The FaD switches off the electrical power that is necessary to close the clutches of all actuators. This option is used as a safety measure during flight testing. It also converts the aircraft into an ideal test bed for flight control system development as it allows safely flying with experimental software versions. However, the final objective is to have a certified AFCS that fulfils all safety requirements.

After a concept and definition phase, the S15 prototype was modified (power supply, installation of flight test equipment) and the flight control system with all its components (sensors, computer modules, actuators, control panel etc.) was integrated. The functionality was incrementally increased. Flight tests started in August 2010.

3 Automatic Flight Control System

This section gives an overview on the AFCS. The AFCS has full authority in all axes and is a safety-critical system. Figure 4 schematically shows the mechanical linkages of the flight control surfaces that are used by the AFCS. The required full authority, the high-precision trajectory tracking during measurement tasks and the gust load alleviation for payload stabilisation result in a controller bandwidth that is significantly higher as for conventional general aviation autopilots. It has to be assured that the flight control laws do not negatively couple with structural dynamics. The low level flight (LLF) and automatic takeoff and landing (ATOL) are the driving factors for the required system reliability. A redundant and fault-tolerant system is necessary to cope with the requirements for the system reliability. A fast decoupling function (FaD) is needed to instantly disconnect the actuators from the primary controls of the aircraft. The FaD is necessary to cope with unknown obstacles (collision avoidance) since the AFCS has no forward looking capabilities, and since it is also needed for the flight tests of the demonstrator as long as the reliability of the AFCS has not been fully proven. The FaD needs to be completely independent from the AFCS, and its reliability must be at least equal to the reliability required for the AFCS itself.

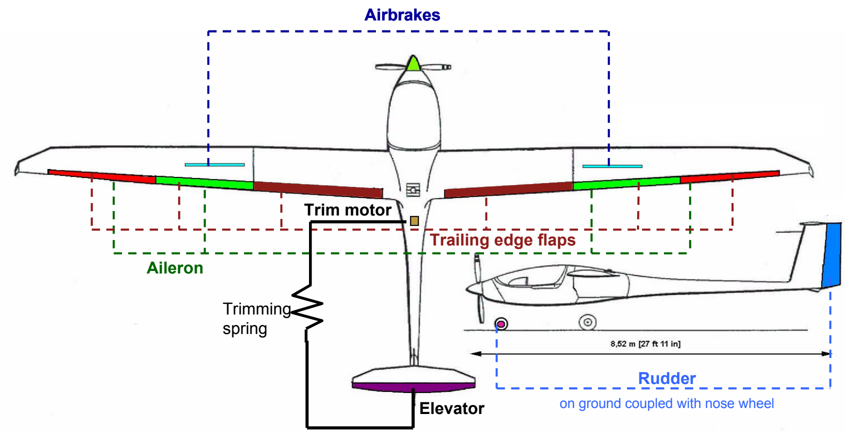

Fig. 4 Mechanically linked Flight Control Surfaces

3.1 Safety Objectives

The safety objectives for the AFCS design are derived from the FAA advisory circular AC23.1309-1C for “Class 1” category aircraft, see [2]. “Class 1” stands for aircraft with single piston engines below 6000 lbs takeoff weight. This leads to a software development assurance level (DAL) of class “C” and requires that the probability of a catastrophic failure condition must be extremely improbable, i.e. its occurrence has to be less than 10^{-6}/fh.

In order to support the planned certification of the AFCS as part of a utility aircraft, a development process for complex, safety-critical systems according to SAE ARP has to be established and the software has to be developed accordingly.

3.2 Flight Control Functions

The AFCS shall provide high precision flight path control for an utility aircraft that is used for airborne measurements and surveillance. The lateral and vertical accuracy have to stay within a few meters. This requires high-precision sensors, a fast and accurate actuation and well designed flight control laws. In addition, the AFCS shall stabilize the aircraft attitude in atmospheric turbulence as it is required for certain payload sensors. Hence the AFCS shall support the following tasks

- Ferry flights and flights to and from a mission area;
- Scan patterns, i.e. geo referenced scanning of a mission area following a predefined pattern, e.g. for photogrammetry or search missions;
- Observation of geo referenced lines: e.g. to survey streets, rail roads, rivers or power lines;
- Observation of geo referenced points: e.g. to monitor power plants, airports etc.;
- Observation of movable objects: e.g. observation of cars, ships or animals.
- Low Level Flight (LLF), i.e. geo referenced flights down to 20m above ground with precise tracking of height commands, e.g. for geo exploration.
- Automatic takeoff;
- Automatic landing including rollout and taxi.

The aircraft shall be able to perform a flight completely automatically with no intervention of the pilot. A gust alleviation system shall stabilize the aircraft and its payload in gusty conditions and shall improve the working conditions for the crew. It also increases the measurement durations when convective turbulence levels raise during the day and gusts become critical to a certain sensor types.

When the AFCS is disconnected, the pilot must take control of the aircraft. An auto-trim function trims the aircraft such that the pilot can take over without significant transient control forces in the pitch axis.

Figure 5 gives an overview on the functional flight control architecture. The pilot can enter high level commands via the Automatic Flight Control Panel (AFCP). It can be either tactical commands (altitude, track, climb or descent) by using the buttons and knobs or by providing a detailed flight plan for a complete mission. The flight path and the lateral navigation control laws and mode logics compute the trajectory commands using energy principles for longitudinal flight path control. The inner loops generate the control surface commands taking the specific flight dynamics of the S15 aircraft into account. The basic pitch inner loop can be supplemented with gust load alleviation functions that use the trailing edge flaps:

1. closed-loop control based on the vertical load factor and
2. feed forward control of the wind angle-of-attack which requires the installation of a 4.5 m boom with angle-of-attack sensor.

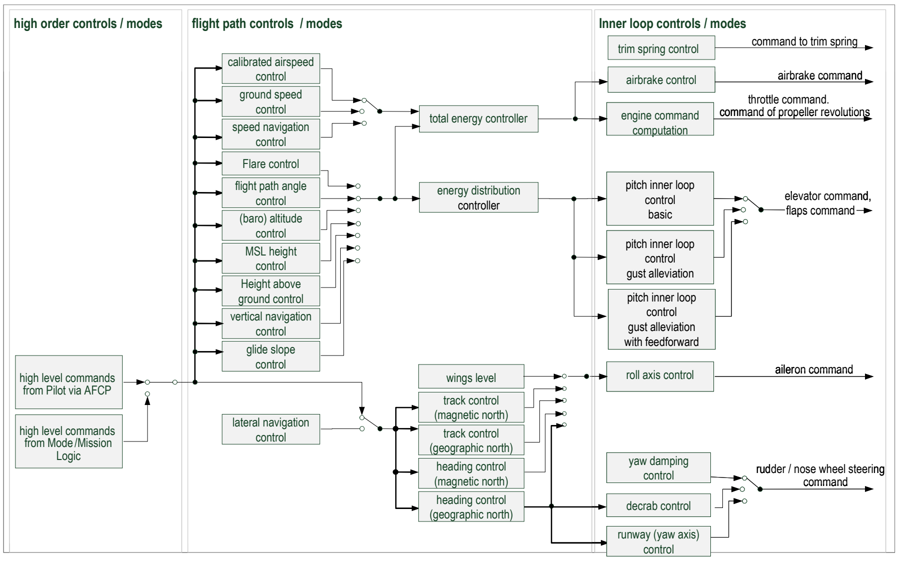

Fig. 5 Flight Control Law Architecture

3.3 Automatic Flight Control Panel (AFCP)

Figure 6 shows the Automatic Flight Control Panel (AFCP) that represents the interface between the pilot and the flight control system. The AFCP is specifically designed for the S15. The pilot can select various operational modes and enter command values for height, heading, speed etc. Alternatively, he can enter a complete mission profile (waypoints, heights, speeds, origin, and destination) that is planned before the flight and entered via an USB stick. To assure that the AFCS has correctly received the mission data, the pilot has to validate and confirm the data that are displayed on the AFCP.

Fig. 6 Experimental Automatic Flight Control Panel (AFCP)

3.4 Platform

The AFCS is based on the Flexible Avionics Platform technology that is developed at ILS, see Ref. [8, 9]. The Flexible Avionics Platform provides an advanced software architecture with the following characteristics:

1. Compared to state-of-the-art concepts like the so called Integrated Modular Avionics (IMA), additional abstraction layers are introduced to the system software architecture. They do not only cover the basic communication and the local operating system of individual modules but quasi the complete system operating management of the distributed AFCS, i.e. the layers of *aggregate unification*[5], *voting/monitoring*, *reliable broadcast*[6], *consensus generation*[7] and

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[5] Aggregate unification: Bringing heterogeneous aggregate signals into a uniform, predefined representation.

[6] Reliable broadcast: see Ref. [17].

[7] Consensus generation: Establishing consensus within the Flexible Avionics Platform instance, see [9].

operation control of the complete system including sensors and actuators. These layers abstract the complexity of the complete system architecture and simplify it to a virtual simplex system from the perspective of the so-called *application*, i.e. flight control laws. Consequently, the complexity of the system is fully transparent to the flight control laws.

2. The *middleware*[8] is based on generic mechanisms. Every instance of the middleware and the communication layers can be generated by means of specialization. The specialization process is based on high-level inputs from the system engineer such as the definition of the overall system architecture. If this definition exists, all software parts, which are necessary to specialise the middleware and the communication layers, are instantiated automatically. A tool suite is used to execute this auto-instantiation. It is based on a multi-layer meta model of the platform management functions and instantiation rules.

Those technologies are applied in the LAPAZ project. They allow a highly efficient development of the AFCS by a high degree of automatic instantiation of the system management functions of the redundant AFCS.

3.5 AFCS Architecture

Requirements on the AFCS architecture were derived from a functional hazard analysis (FHA) that was performed as one of the first tasks. As required in [2], “no single failure at airplane function level will result in a catastrophic failure condition”. Figure 7 shows the resulting architecture of the automatic flight control system (AFCS). It consists of two Core Processing Modules (CPM, see Fig. 8), two Input Output Modules (IOM), a dual redundant system bus (Flexray), and the required aggregates (sensors, actuators, HMI). Each CPM has full access to all aggregates. The blue and the red colours indicate which part of the power supply provides electric power, see section 3.6. The yellow colour indicates that the Inertial Navigation System (LITEF LCR 100) is connected to both power supplies, and can be powered either by the red or the blue one. A detailed description can be found in Ref. [6, 7, and 8].

Each CPM and each IOM has internally two lanes (lane A and lane B) that perform the same tasks simultaneously. A failure of one lane can be detected by monitoring and comparing the data of lane A and B. If the data differ, a failure is detected and the module passivates itself (fail-passive behaviour for internal faults). If one of the CPMs fails, its functions will be taken over by the other CPM. Sensors and actuators are connected to the platform instance via the IOMs that have interfaces for Flexray, CAN, serial RS232 and ARINC 429 data buses, as well as for discrete and analogue signals. Due to the modular architecture of the system, an expansion from duplex to triplex redundancies is easily possible.

[8] Middleware is software that mediates between an application program and a network.

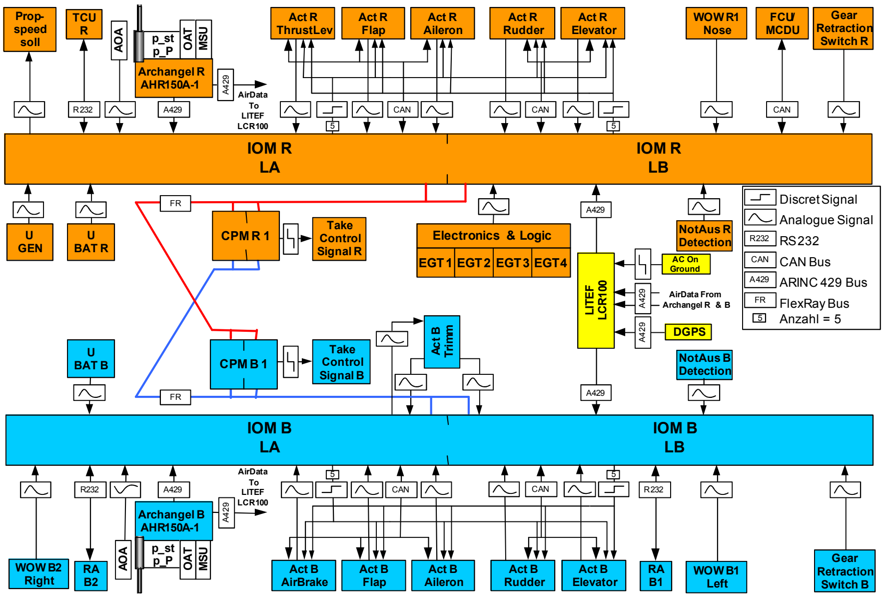

Fig. 7 Redundant, distributed and modular Hardware Architecture of the AFCS

The task of the IOMs is to perform the interfacing to all external components (sensors, actuators, instruments, etc.), to convert, consolidate input and output signals and to provide them to the internal platform network, and to contribute to the platform management. The CPMs perform the key tasks of the platform management as well as the system functions, here the flight control functions that are implemented in form of the flight control law software.

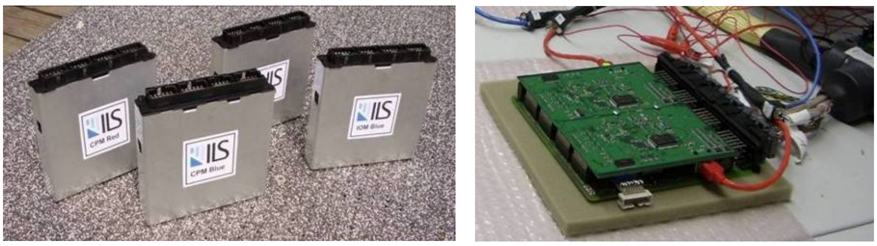

Fig. 8 a) Core Processing and Input Output Modules; b) CPM during tests

3.5.1 AFCS Sensors

The system is equipped with high performance, state-of-the-art sensors. Most of them are certified. Duplex redundant sensor signals are voted to assure that sensor failures are detected and do not affect safety critical function. In order to guarantee the availability of attitude control after one sensor failure, the signals of three sources are voted. The following sensors are installed (see Fig. 7):

- Two Attitude and Heading Reference System (AHRS), Archangel AHR 150A-1, each coupled to static and dynamic air pressure (p_st, p_P), outside air temperature (OAT) sensors, and a magnetometer. Those signals are transmitted to the Inertial Navigation System via an ARINC 429 bus.
- One Inertial Navigation System (LITEF LCR 100) supplemented with a Global Positioning System (GPS) that includes satellite based augmentation (EGNOS) for enhanced positioning accuracy. The system is used for navigation as well as for takeoff and landing. So, the airplane can operate on any airfield independently from navigation aids on the ground.
- Two angle-of-attack (AOA) sensors,
- Two laser altimeter (LA) that support vertical guidance during takeoff, low level flight, final approach and landing.
- Simplex weight-on-wheel sensors (WOW) at each landing gear strut. The main landing gear is equipped with a ground contact sensor. At the nose wheel, the compression of the spring is measured.
- The Turbo Control Unit (TCU) that is part of the ROTAX motor transmits engine speed and throttle position and the exhaust temperature sensor.
- The actuator positions are used to estimate the control surface deflections.

To cover the safety and reliability requirements of the AFCS for a utility aircraft S15, the sensor system provides triplex redundancy of all essential inertial data and duplex redundancy of all air data. To incorporate a functional demonstration of the ATOL capabilities, the system provides also navigation data. For cost reason these data are currently only simplex. However, provisions are there for realising triplex redundancy. The reliability of GPS data and their use for landing is another open issue.

3.5.2 Actuation

The flight control system actuates the following controls: all six wing control surfaces (ailerons and flaps), elevator, rudder, airbrakes, throttle, propeller speed, and elevator trim. In total, ten actuators are necessary for actuation: two redundant independent actuators for the ailerons, the trailing edge flaps, the elevator, and the rudder, one actuator for the airbrakes and the throttle. The propeller speed is commanded by the existing controller (P-120-U). The electric motor of the standard manual flight control system is used for elevator trim. Nose wheel steering is achieved with the rudder actuator as nose wheel steering is linked with the rudder actuation when the aircraft is on ground.

The ten identical electro-mechanical actuators are integrated into the existing mechanical flight control linkage, see Fig. 10. The actuators consist of an electric motor, a Harmonic Drive gear, a clutch, a power electronic, and resolvers that measure deflection angles at the motor and the actuator shaft, see Fig. 9. The actuator is controlled by the IOM via the actuator control loop (commanded by the flight control laws) and diverse monitoring mechanism. Each actuator provides a

peak torque of 60Nm, a maximum continuous torque of 23Nm. The maximum actuator shaft rate is 35 rpm (210 deg/s). The dynamic behaviour of the actuator especially for small deflections is highly nonlinear. A detailed model was developed for the design of actuator control laws, see Ref. [14].

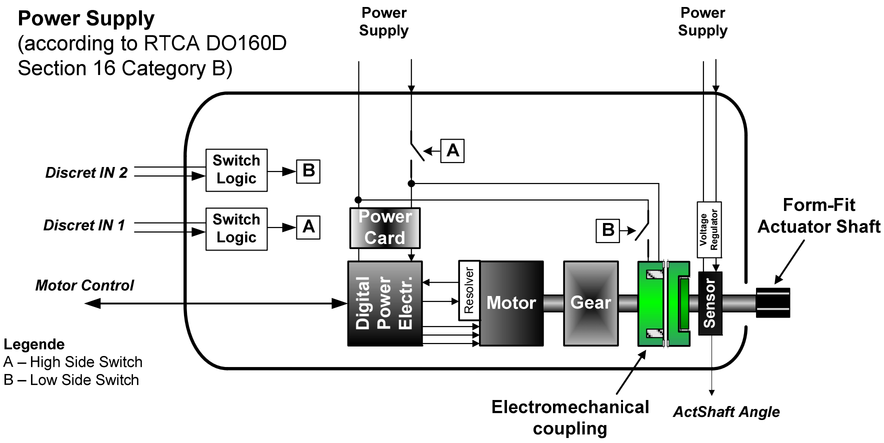

Fig. 9 Actuator architecture

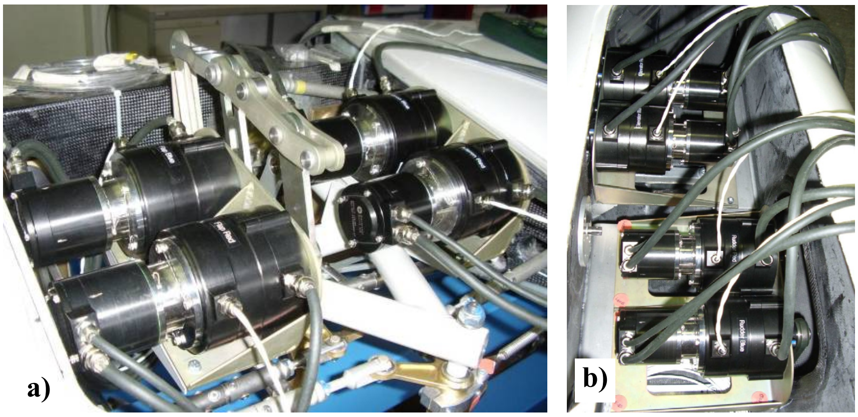

Fig. 10 Integration of a) two flap and two aileron actuators at the inner wing over the engine and b) two rudder and two elevator actuators in the fuselage

3.5.3 Flight Control Law Software

In order to develop a precise and highly dynamic flight control system a realistic flight mechanical simulation model of the aircraft is needed for flight control law design and testing. The flight control laws (FCL) development is based on a high-fidelity simulation model that is described in Ref. [10]. Details for controller design are given in Ref. [11, 12].

The flight control law (FCL) software is developed in a Matlab®/Simulink® environment using Stateflow®. The FCL source code is automatically generated by using the Real-Time Workshop® Embedded Coder™. After compilation, executable code is loaded onto the CPM, in total four times; one for each CPU, see Fig. 11.

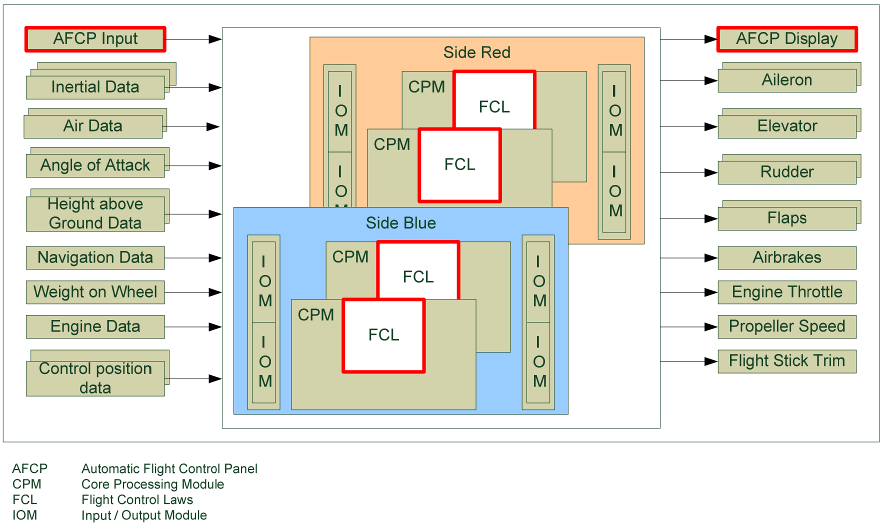

Fig. 11 Integration of FCL into the AFCS

A major challenge is to develop, certify and produce the software for such a safety-critical system at competitive and affordable cost for civil applications. The use of modern standard components from the automotive industry and the definition of a stream-lined system development process are key elements. More details of the LAPAZ development process can be found in Ref. [13]

3.6 Power Supply System

The power supply system is duplex redundant and has a symmetrical design. It provides the same redundancy level as the AFCS. One alternator and two batteries ("blue" and "red") generate the necessary power, see Fig. 12. In the figure, the critical and highly redundant FaD switch that disconnects the power from the electro-magnetic clutches to disconnect the actuator from the mechanical linkage is depicted in green.

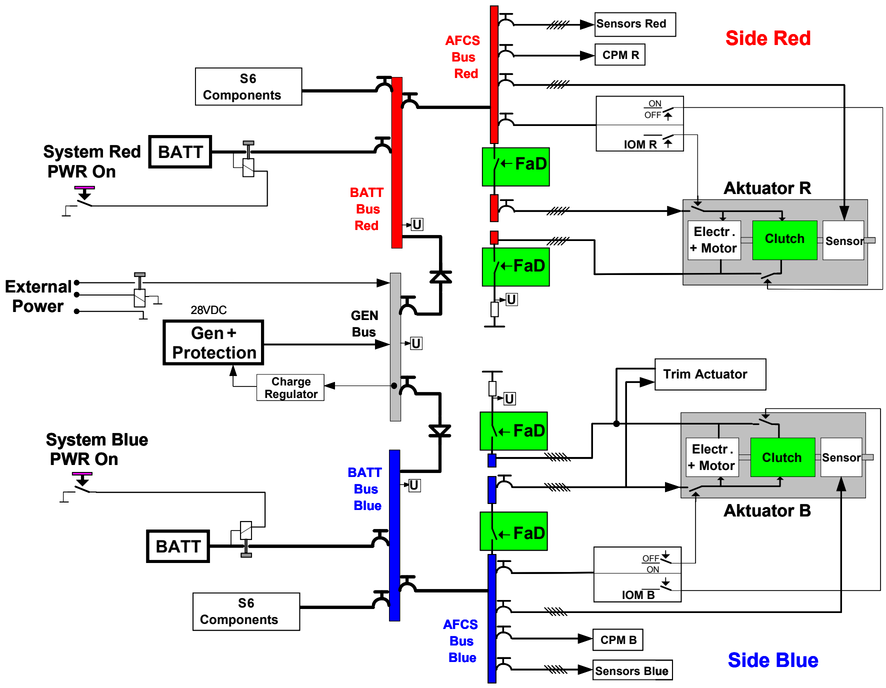

Fig. 12 Electrical Power Systems

4 Testing

Testing of the AFCS functions comprises test on different system integration levels:

- Offline tests during FCL development on desktop PCs;
- Real-time tests in a generic flight simulator;
- Integration tests of the FCLs implemented on the AFCS using an avionics test system;
- Hardware-in-the Loop (HIL) flight simulator tests, see Ref. [13]; and finally
- Flight tests.

In the next sections only the flight tests will be described including the flight measurement system.

4.1 Flight Measurement System

For AFCS flight tests the S15 aircraft is equipped with a flight measurement system that was developed by the Institute of Flight Guidance, TU Braunschweig. It comprises the following components, see Fig. :

- Computer system for data acquisition and data recording that interfaces with 4 RS232 ports, 2 USB ports, LAN, VGA, 4 times 32 analogue channels, 2 CAN bus ports, 8 ARINC 429 input and 4 ARINC 429 output channels, Fig. a;
- Control box that allows the pilot starting and stopping of the system;
- Inertial navigation system (INS) based on fibre optic gyro technology (FOG) with integrated L1/L2-RTK-GPS (IMAR iTraceRT-F200-E), Fig. d;
- Air data boom with angle of attack and angle of sideslip vanes and a 5-hole probe; Fig. c;
- 4 pressure sensors;
- Multiple sensors for control force measurement, Fig. b and e;
- Multiple laser sensors and potentiometers to measure rudder deflections, Fig. e.

The sensor positions are shown in Fig. 14. In addition, a measurement system consisting of a LMS SCADAS recorder and eight accelerometers was integrated for testing structural dynamics, see Fig. f.

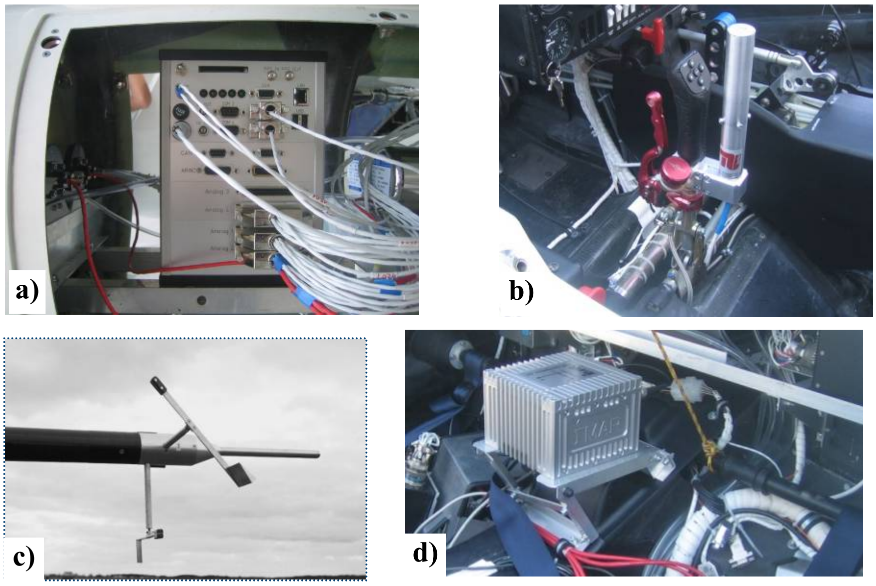

Fig. 13 (a-d) TUB's flight measurement system installed in the S15

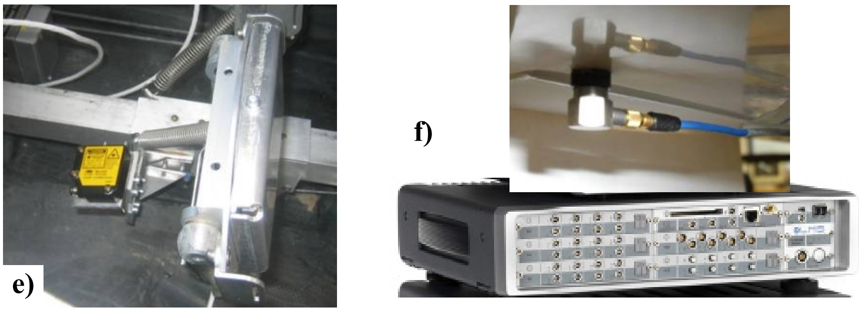

Fig. 13 (e-f) TUB's flight measurement system installed in the S15

Flight test data are recorded with the flight measurement system as well as with a SPY functionality that is part of the AFCS platform instance. The SPY has access to the data base of all AFCS modules during runtime. It is used in flight tests to record selected signals including internal signals of the FCL software as well as the input signals from the sensors and the output signals to the actuators and displays.

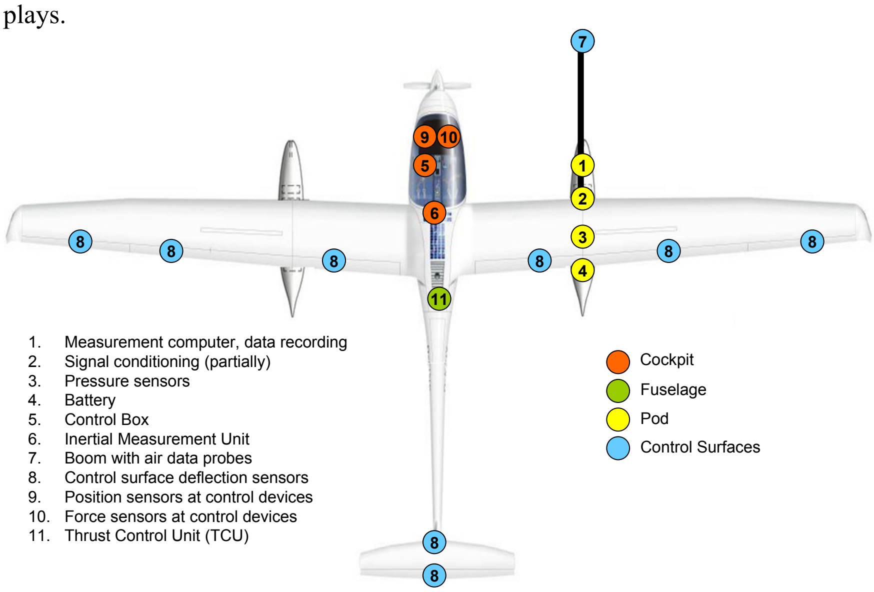

Fig. 14 Sensor location of flight test equipment

4.2 *Flight Testing*

The flight tests are performed under a Permit to Fly according to Annex II of EC regulations 216/2008. The flight test program comprises test for identification of the flight mechanical rigid-body and flexible aircraft model as well as AFCS tests. Specific identification tests were performed, in which the structural dynamics were excited with sweeps and sinusoidal signals on the elevator, aileron, rudder and trailing edge flaps by using the AFCS as a signal generator; see Ref. [15, 16]. AFCS flight testing started in August 2010. Since then, twelve software versions have been tested until now in approximately 100 flight hours. New functions were introduced incrementally and improvements of the tested functions were implemented if necessary. On March 22nd, 2012 a major project milestone was achieved with the first automatic landing at the airfield Neuhardenberg, see Fig. 15.

Fig. 15 S15 during first automatic landing at Neuhardenberg on March 22nd, 2012

The next milestone was a complete automatic mission from takeoff to touchdown at Strausberg on November 23rd, 2012, see Fig. 16. The AFCS controlled the aircraft during a right hand traffic pattern from takeoff run until touchdown.

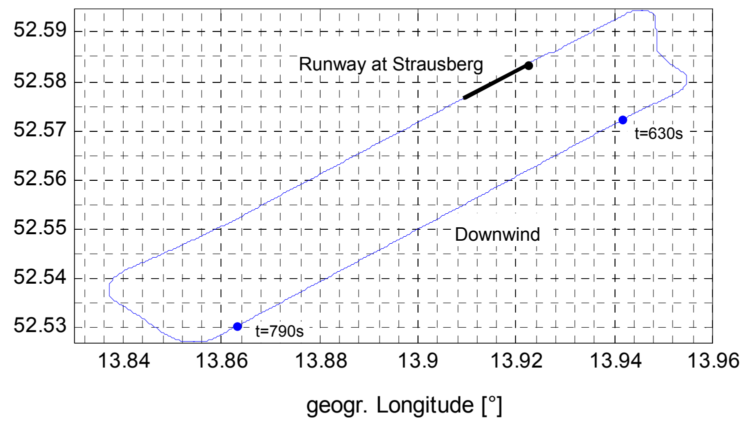

Fig. 16 First fully automatic mission; traffic pattern at Strausberg on November 23rd, 2012

Figure 17 shows the calibrated airspeed (black) and the altitude (blue) over time for takeoff run, rotation, climb to approximately 320 m height, descent, landing approach, touchdown and deceleration (braking was done manually). Wind speed (5kts from 180° at takeoff) and turbulence level were low.

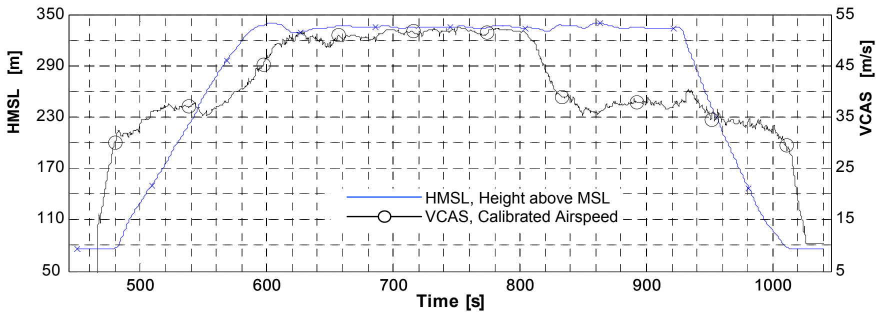

Fig. 17 Height above MSL and calibrated airspeed during first fully automatic mission

On the downwind leg (between t=630s and t=790s), the root mean sqare (rms) of the vertical position error of 1.17 m and the lateral position error rms of 0.91 m are indicating the excellent flight path tracking accuracy, see Fig. 18.

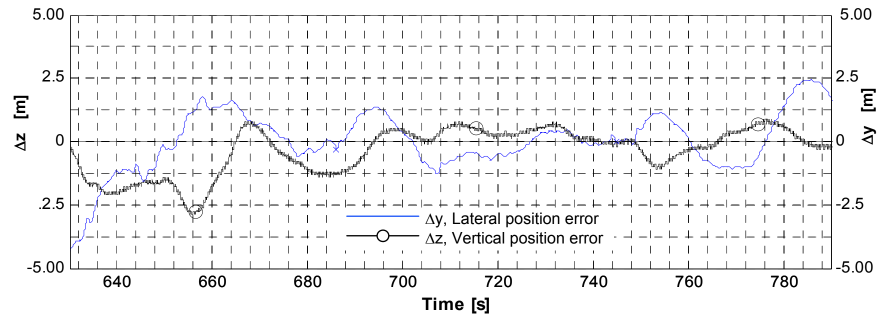

Fig. 18 Vertical and lateral position error during first fully automatic mission

The next major step will be testing of the feed-forward gust load alleviation using a 4.5 m boom at the wing for measurement of gusts in front of the airplane, testing of a glider-like landing mode by using the airbrakes dynamically and flight at low altitudes.

Conclusions

An automatic flight control system (AFCS) that supports or even replaces the pilot during airborne reconnaissance, surveillance, exploration, and measurement tasks has been developed for the light civil utility aircraft STEMME S15. The development, certification and production of such a safety-critical system and its software according to the certification specifications EASA CS23 at competitive cost is a major challenge. The definition of a modular and scalable system architecture, the use of modern standard electronic components, and the definition of a streamlined system development process are the key elements for success. The LAPAZ project has demonstrated AFCS functions, hardware and software. Although some functions, such as gust load alleviation, still have to be validated by flight tests, the focus is moving toward the implementation of an efficient system development process that targets certification of the flight control functions and the AFCS according to a development assurance level (DAL) of class “C”.

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