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A Proposal for a Fully Distributed Flight Control System Design

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Abstract - Since the delivery of the first A320 airliner with a Fly-by-Wire Flight Control System (FCS) in 1988, aircraft avionics architecture evolved significantly. Federated Architecture applied in the A320 family of aircraft presumed one computer per function. Limits regarding weight and space availability were reached and new generation of aircraft designed in early 2000s were equipped with Distributed Integrated Modular Avionics Architecture consisting of shared hardware resources running separate software modules according to aircraft priorities. Flight Control Computer functions were assumed by the Flight Control Module. While reducing the cost, weight and number of computers on board the aircraft, problems with troubleshooting and system modifications emerged. Proving that critical Systems perform within certain certification safety requirements became infeasible due to unpredictable dependencies between software modules. Abovementioned problems are addressed in this paper with a proposal of a Fully Distributed Flight Control System (FDFCS) design. Main contribution is that aircraft stability and trajectory control logic is distributed to a network of independent Control Units (CU) collocated on actuators collaborating to control the aircraft with respect to common goal. This paper outlines design for FDFCS and its CUs. Problems that distributed FCS implies and solves are identified. Finally, requirements for planned FDFCS Hardware in the Loop Simulator are set.

I. INTRODUCTION

The aircraft avionics architecture is mainly composed of processing modules and communication buses. It supports flight control and management, navigation, communication, weather systems, collision-avoidance systems, and aircraft health monitoring systems. Avionic systems represent about 40% [1] of aircraft costs for civil aircrafts, and more than 50% [2] in military aircraft. It is evident that an avionics architecture is central part of the modern aircraft.

Flight control system (FCS) consists of flight control surfaces, cockpit controls and connecting linkages. Fly-by-wire (FBW) Flight Control System replaces mechanical linkages with transducers, wires and actuators. A reliable communication network provides the backbone of every FBW system. Electrical components comprising the FBW system are integral part of the avionics architecture. FCS performs critical applications as flight stability augmentation, flight guidance and envelope protection. Therefore, the FCS system must satisfy safety and dependability requirements, and meet performance specifications for certification. Possible implication of FCS failure are severe.

Real-time performance of FCS control software and communication network must be assured. Aircraft FCS must deliver the right commands to the control surfaces at correct time in coordinated fashion. Even in the event of failure of one part of the system, the rest of the system must continue to work within certain specification called degraded mode. Communication network latencies that are defined by wiring and network infrastructure layout have to be accounted for during system design to assure real-time performance. During normal aircraft operation, aircraft equipment may fail. Dependability of FCS is dictated by the avionics architecture. Unpredicted events such as loss of a part of the communication system or failure of any of the flight control computers must not have catastrophic impact on the performance of the system. Performance during such events must be validated for system certification.

Safety analysis must be performed in accordance with Advisory Curricular AC25.1309, for System Design and Analysis [3]. The part 25 airworthiness standards of the FAA Federal Aviation Regulations are based on the fail safe concept, which considers the effects of failures and combinations of failures, both detected and latent, in defining a safe design. Requirement of AC25.1309 is that airplane systems must be designed so that the occurrence of any failure condition, which would prevent continued safe flight and landing of the airplane is extremely improbable [3].

Special care while designing the software for the FCS computers should be taken, to assure that similar software is not used on different computers. Using dissimilar software minimizes the risk of common error that could cause all computers to underperform or fail at certain unexpected condition. The concept is referred to as "Similar Redundancy" and it is also applied to hardware design of FCS computers.

Dependability, Safety and Real-time requirements define main constraints while designing the FCS. The designer must also consider other parameters as ease of maintenance, troubleshooting, upgrades and modifications, and account for future growth in required system functionality [4]. Focus of this paper is to provide concept of Fully Distributed FCS and to set requirements for the system simulator. The first stage of research and requirements to build the simulator to test the proposed control concept are described. The concept block scheme of the needed simulator will be described in more detail.

II. AVIONICS ARCHITECTURES AND FLIGHT CONTROL SYSTEM

We can separate two different approaches for the design of the avionics architecture. Federated avionics architecture (Fig. 1) was used on commercial aircraft until 1990's. It is characterized by the one function - one computer concept. Each aircraft system is run on separate dedicated hardware resources connected to its sensors and actuators. Major advantage of such an approach is that dependencies between systems are easily identified. Troubleshooting of federated systems is simplified. Real-time behaviour for FCS can be proven and time delays can be measured. Certification requirements for the federated system are easily tested.

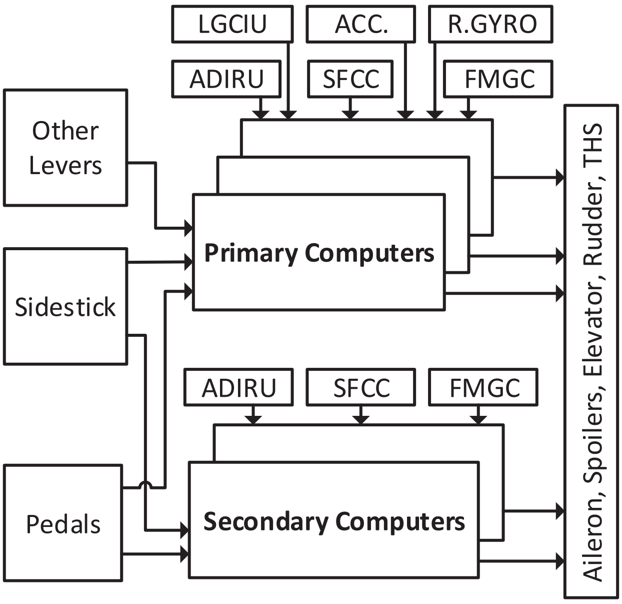

Figure 1. A320 Flight Control System (partially displayed), Federated Architecture

Major disadvantage of a federated system is a large number of different line replaceable units (LRU) comprising the system. From the operator standpoint, this causes difficulties since large number of components need to be stored on stock for replacement purposes. From the manufacturer standpoint, each new subsystem adds weight to the aircraft, reducing passengers and cargo capacity.

With the growing needs for avionics computing resources, the Federated Architecture reached its weight and complexity limits, and distributed integrated modular avionics architecture (IMA) was developed (given in Fig. 2). The IMA concept is based on sharing of hardware resources called IMA processors that are running separate software modules for each system. One IMA processor can run several modules with different priorities. Architecture development is accompanied by introduction of high-speed common communication channels. Common input-output interfaces are introduced for sensors and actuators.

Major advantage of the IMA concept is the reduced number of computers and communication data cabling on-board the aircraft [5]. From the manufacturer perspective, this advantage allows for reduced aircraft weight and required engine power. Operators need to store less LRU's for repairs. However, many disadvantages arise from sharing resources. Determining dependencies between systems running on common hardware resources and common data channels is difficult. Troubleshooting is also proving to be complicated. Testing real-time behaviour and measuring time-delays for FCS is almost infeasible. All said, demonstrating fulfilment of certification requirements for the IMA system is a major issue.

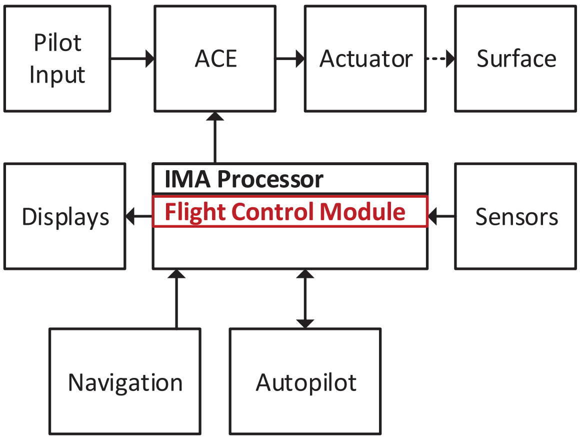

Figure 2. Distributed IMA (full lines represent network channels, dashed line presents mechanical linkage).

FCS, within the Federated architecture, is controlled by five separate computers [6]. Each computer has a control and monitor channel. Upon disagreement between channels, the affected computer is passivated while the next highest priority computer takes control. It is possible to fly the aircraft with only one functioning computer.

FCS within IMA is a software module. Upon failure of one IMA processor, the other one or a backup IMA processor loads the necessary software module and takes over the functions of the system. Meanwhile the actuator control system (ACE) provides a direct link from pilot controls to control surfaces [7].

III. MOTIVATION FOR A FULLY DISTRIBUTED FLIGHT CONTROL SYSTEM

A proposal for fully distributed flight control system (FDFCS) design is given in this article. The authors believe that FCS functions can be distributed down to the actuator control level. FDFCS would be a network comprised of actuator collocated control units, collaborating to control the aircraft with respect to a common goal. Major advantage of this approach is moving the requirements for certification of FCS from IMA to separate subsystem. Although increased number of embedded devices is required on-board the aircraft, the overall number of high power, high price computers can be reduced. The embedded devices for FDFCS should be collocated or installed near the control surface actuators, and have relatively low processing power thus low unit price. Furthermore, control units (CUs) can be of same type for all positions thus reducing the number of replacement units necessary for operator to store. The reduction in data and control wiring by distributing the FCS functions to actuator level is significant. Integrating micro electro-mechanical sensors (MEMS) into each CU can reduce communication loads and the amount of data wiring for sensors. Redundancy of the overall system is exponentially higher. The proposed system is described in detail in the following chapter.

IV. FULLY DISTRIBUTED FLIGHT CONTROL SYSTEM

A fully distributed flight control system is defined as one where all the FCS roles and functions are distributed to the network of embedded CUs located on, or near the control surface actuators. Control units have to be networked in a secure and reliable way for the FDFCS design to operate safely. The choice of the connection standard is not proposed for the system; however, the controller area network (CAN) will be used as an example to demonstrate how safety and certification standards can be assured. Two separate CAN networks are assumed for redundancy. Terminating the two networks at different parts of aircraft assures that no part of the system is left unconnected for the case when the communication lines break at one point as shown in Fig. 3

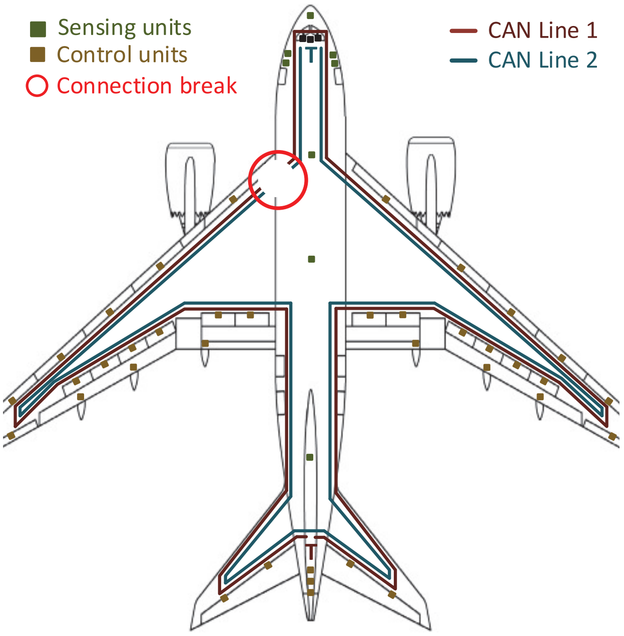

Figure 3. FDFCS CAN network routing with separate termination points for case of connection break near left wing root

Additionally provisions within the CUs have to be made to make actions in case of connection loss to ensure minimal intermission of the disconnected unit to the operation of the rest of the system and the controllability of the aircraft. This can be achieved by implementing automatic passivation of the affected control surface in a neutral position, on total connection loss.

The proposed design of the CUs consists of three embedded systems integrated into a single case called simply units. The term units will be used in this paper to avoid confusion with the term module used to describe software modules run on IMA. The primary embedded unit within the CU performs FCS functions and roles, and will be referenced from here as flight control unit (FCU). The secondary embedded system, referenced as external override unit (EOU), has the sole purpose of overriding the FCU outputs on a certain event, and allowing the remote control of the corresponding actuator.

The power regulation and communication level translators are doubled and not shared amongst the units, removing any chance for communication loss on both devices within the CU caused by translator or rectifier failure. The third embedded system is the actuator control unit (ACU) or the executive unit. The role of this unit is to manage actuator(s) connected in a way ordered by FCU and when overridden, the EOU. The unit uses both power provided by FCU and EOU as a redundancy to assure that when at least one unit is operating, the ACU has power available. Figure 4 shows the proposed design for the CU.

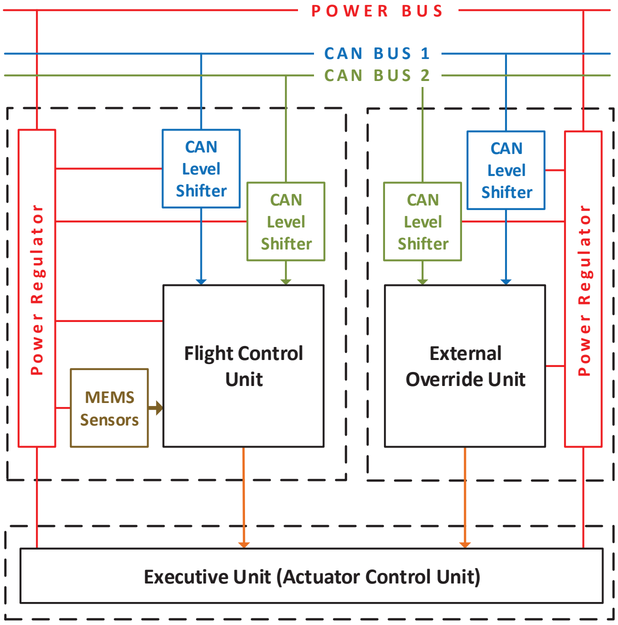

Figure 4. Proposed CU design for FDFCS

MEMS sensors are not yet precise enough for aviation purposes [8] to serve as the only input of positioning data instead of the sophisticated and expensive inertial reference units (IRU). However, it can be expected that they will reach the required specifications in future [9]. Considering the low price of MEMS sensors, it is reasonable to propose the integration of MEMS sensors within each CU. Low cost and low precision MEMS sensors within every CU can be used to estimate positioning data for short periods of time. Higher precision IRU should be used to correct MEMS sensors positioning on regular intervals. This approach helps to reduce the traffic on the communication network that would be caused by constant positioning data transfer from the IRU, GPS receivers and other sensory units to the CUs. In addition, the number of IRUs on board can be reduced once the precision of MEMS sensors rises to the required level. Theoretically, once the satisfactory precision can be maintained for the time aircraft requires to complete the precision approach, the aircraft should be fully capable to continue the approach to the airport (runway) in case of IRU failure at the most critical moment, or at the beginning of the approach to the airport (runway).

Control system should not be solely time triggered or event triggered [10]. It would be beneficial that sensory units as GPS receivers and IRUs broadcast data on the network on regular intervals. That would assure that all the units have the positioning data corrected at certain regular interval. CUs should communicate between each other on a specific event, only when communication is required to perform FCS functions. However, provisions in each node have to be made to protect the buses by limiting the data bandwidth consumption [11].

All units need to transmit two kinds of data. The first kind would be data request, and the second data send. Units should be able to request and send data from and to other units such as control surface position or positioning data. Such a request allows that the monitoring function of one unit can be assigned to any other unit on the system, facilitating fault detection. When a certain number of units on the system detect a malfunction in operation of the monitored unit, the EOU should be activated and take control of the control surface.

In the emergency event of loss of many systems necessary for the normal or the automated operation of FCS, the degraded mode of operation should be available. The degraded control mode must allow direct control of the units. Direct control should transfer pilot commands to the control surfaces without any interference. Under no circumstances like other systems failure or corruption, should direct mode of operation be affected. These dependencies have to be designed in the system and validated.

The normal control mode should improve the stability of the aircraft and protect the flight envelope, independent of weather the aircraft is operated by a pilot or guided by the flight management system (FMS) and controlled by the autopilot. When normal control mode is active, CUs must cooperate to control the aircraft. For instance, the port and starboard ailerons and spoilers should differentially deflect in a way to prevent unwanted yaw. Communication is required for whichever motion the surfaces are coupled and produce total effect. To assure coordinated outputs, cooperation between units should be organized. Massive voting can be applied to achieve the desired result. However, for the system to be fully distributed there should be no central unit assigned to decide on the control surface positions. The network and its units should be self-sufficient to provide for all roles of FCS.

V. REQUIREMENTS FOR THE FDFCS HIL SIMULATOR

In order to validate the concept of the proposed FDFCS system a simulation has to be done. To improve the quality of the simulation a real time hardware in the loop simulation (HIL) is always recommendable. In order to make such a simulation certain requirements have to be fulfilled. An accurate aircraft and flight model including atmosphere and aircraft engines have to be simulated in real-time using appropriate simulation software like Matlab/Simulink, and the communication network with the CUs has to be implemented as a real system is this case. In such a simulation setup the control hardware will receive accurate inputs and computed control outputs will be forwarded to corresponding actuators and act as a feedback to the simulated aircraft, as shown in Fig. 4

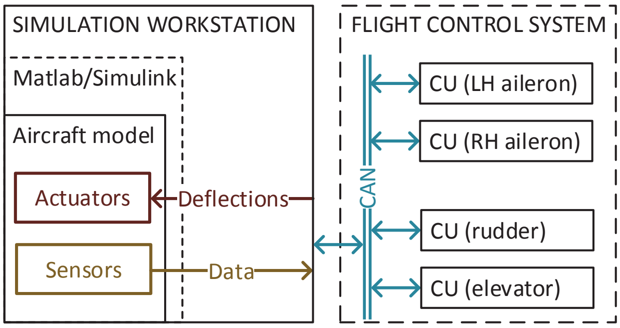

Figure 4. HIL simulator for the FDFCS showing the simulation workstation and hardware side of the system embedding the FCS

Envisaged HIL simulator design will use the CAN network to connect the needed components. A simulation workstation equipped with an aircraft model running in Matlab/Simulink will be used to simulate the aircraft in flight ensuring realistic sensory data. The simulation workstation will be equipped with a CAN interface to establish communication with several CUs. Each CU will be assigned to control one aircraft control surface.

VI. CONCLUSION

The embedded CUs will be designed so they will be able to run the FCS. CUs will be running control laws necessary to control the simulated aircraft control surface actuators. Needed aircraft data sensors like air data unit, inertial reference unit, and GPS receiver will be emulated in Matlab/Simulink to ensure needed realistic sensor measurements. The dynamics of the actuators controlled by CUs, will also be emulated in Matlab/Simulink as part of the aircraft model. Finally, the equal processing power centralised control FCS will be developed alongside, to serve as a reference for comparison of the centralised and fully distributed system. Another important requirement is detailed logging and analysis of data traffic in order to create procedures to enable certification tests of the proposed architecture. Additionally, these data logs will be used for in-depth performance analysis of the distributed control architecture. Conclusion

Distributing the FCS logic to actuators removes the need for any sophisticated computers performing FCS function in the avionics bay. Routing of sensory and data wiring is unnecessary, resulting in reduction of aircraft weight. Designing the units to be universal by modifying their control purpose depending on the installation functional item number, allows for storage of minimum number of LRU's for system repairs. However, the issue of unwanted similarity arises and needs to be addressed within the software. The complexity of the system reduces significantly especially because of integrating MEMS sensors into the CUs. Real-time behaviour is defined by the network but should be analysed for the proposed concept of control that mandates voting and data sharing.

However, fitting CUs directly on or near the actuators surely reduces latencies caused by usual over the network control of actuators. The ease of troubleshooting of the system is expected by introduction of fault detection and self-testing functions, and will be further explored.

The proposed distributed FCS system rises many questions about the choice of the appropriate control concept, dependability, implementation of fault detection and dependencies between control units. The next step in our work is to build a dedicated HIL simulator using the Matlab/Simulink environment to answer these open questions and estimate the benefits and disadvantages of the proposed architecture.

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