Technologies for Distributed Flight Control Systems: a Review

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Abstract - This paper reviews the state of the art (SOTA) in distributed flight control technologies using publicly available, scientific and technical publications. Technological developments, such as embedded computing and microelectromechanical systems are enabling advanced aerospace-oriented distributed systems. Distributed systems are comprised of a large number of simple elements, each with its own sensing, actuation and control, in order to obtain the desired behaviour. These systems have the potential to be more economic than a centralized system due to the simplicity of individual components, and possibility of using the same production unit for a different role within the system. The challenge with these systems is the coordination amongst nodes comprising a distributed control network. Benefits of distributed architecture are increased robustness trough redundancy and inherent fault tolerance. The SOTA summary comprises a description of challenges in the design of flight control systems with a distributed structure, technologies currently used in flight control systems and also technologies not specifically related to distributed flight control but applicable for the design of future flight control strategies. Described systems and technologies are represented with examples of real systems including swarms of small Unmanned Aerial Vehicles and distributed networks for Fault Detection and Isolation.

I. INTRODUCTION

Recent advancement in aviation requires more and more sophisticated control systems. New control systems are needed for both, air traffic control and aircraft flight control systems. One of the new approaches are distributed control systems which are examined in this paper. The aim of this paper is to provide a survey of technologies developed and deployed for distributed flight control. The need for distributed control systems arises from the demands of today's modern aircraft which contain many subsystems. All subsystems have to work in an optimal way to ensure that all security and economic constraints are fulfilled. To ensure that, new smart sensors and actuators are used. Such smart elements contain a local embedded computer (controller) with data processing and communication abilities comprising a distributed control system. In such a system a significant amount of data processing is done in local embedded controllers and the master control unit has a global overview of the whole system.

There are three possible types of system architectures for a control system in general: (i) Central architecture; (ii) Distributed architecture; and (iii) Federated architecture. A central architecture uses a centralized hardware and a centralized software framework. One computer is used for several subsystems. As all control hardware is centralized, the environment can be controlled very well [1]. Also the maintenance of these systems is easy. All calculations are also centralized. The distributed architecture uses a distributed hardware and distributed software framework. All calculations are finding place in the sensors and the results are transmitted. A central control unit does not exist and all subsystems have to communicate with each other [1]. The federated architecture is a compromise between the central and distributed architecture. It uses a distributed hardware and centralized software. There are more subsystems than in the case of centralized hardware, but fewer than in the case of distributed hardware [1].

A centralized control approach for Flight Control System (FCS) requires a large amount of electrical cables originating at the flight control computer and ending at actuators and control surfaces as shown in the Fig. 1. The issue of larger mass and complexity of centralized FCS, along with the susceptibility of servo control signals and sensory wiring to noise originating from surrounding electrical systems, are the main technical reasons for the development of distributed FCS.

Recent effort in the field of FCS design is directed towards the improvement of safety, efficiency and overall cost [2]. Airbus patented a robust control system that does not need a large amount of cabling and is based on transmitting calculated signals over the data bus in the form of command messages [3]. The idea of the Airbus invention is to use a distributed FCS, organized around a communication bus in which the control function and some monitoring functions are performed remotely at the actuators.

This paper is organized as follows. In the second section, the problem of flight control is described. The third section describes distributed FCS, and proposed methods for system decentralisation and design. The fourth section reviews emerging technologies related to FCS, such as MEMS (microelectromechanical systems) based systems, unmanned aerial vehicle (UAV) swarm control, distributed fault detection and isolation (FDI) and optimisation. Paper ends with a conclusion.

II. THE PROBLEM OF FLIGHT CONTROL

The problem of aircraft flight control is in creating appropriate control inputs to the aerodynamic control surfaces. An aircraft can have primary, secondary and auxiliary control surfaces. Primary flight control surfaces are required to safely control an aircraft during flight and include ailerons, elevators and a rudder (Fig. 1). Secondary control surfaces are intended to relieve excessive control load and include trim and spring tabs. Auxiliary control surfaces improve the aircraft performance characteristics and include flaps, spoilers, speed brakes and slats. These control surfaces can be controlled by a pilot or by an autopilot as given in Fig. 1.

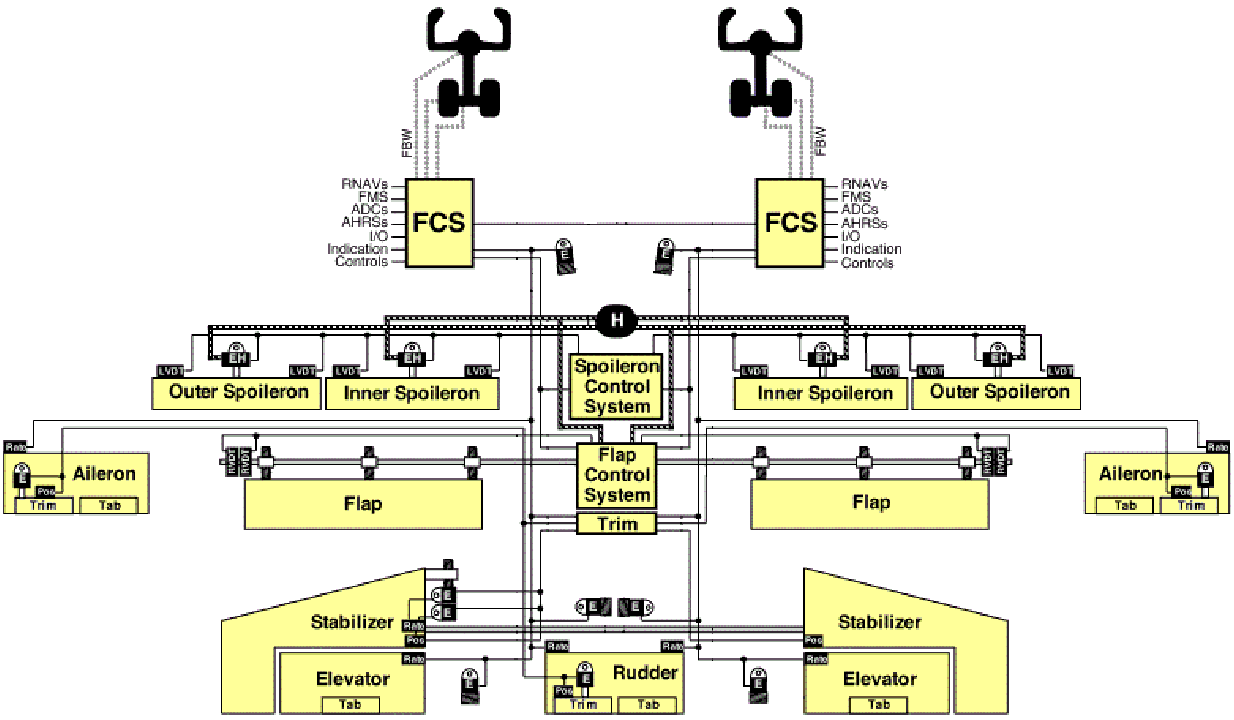

Fig. 1. Aircraft flight control surfaces and architecture [26]

The aim of all mentioned control surfaces is to control the airplane height, speed (*V*), roll (*p*), pitch (*q*) and yaw (*r*) rates, and moments (*L*, *M* and *N*) as presented in Fig. 2.

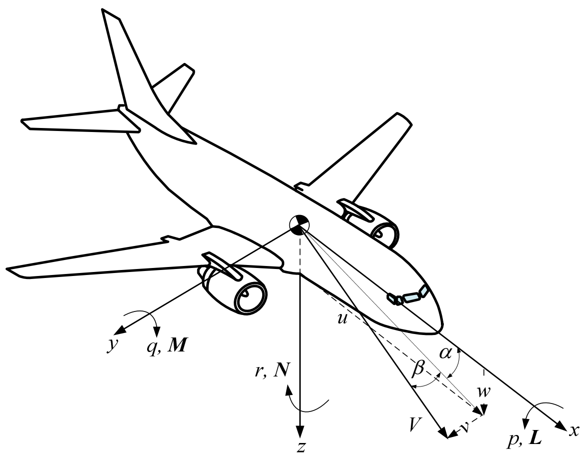

Fig. 2. Body fixed frame with aerodynamic angles, pitch rates and moments

On a modern high speed aircraft, the pilot's control joystick and pedals are not directly linked with the control surfaces. Appropriate systems are in between and augment the pilot control commands applied on the joystick and pedals. Large aircrafts have systems that convert pilot control commands into electrical signals. They are sent via electrical or optical cables to various actuators which can be electromechanical, pneumatical, electrical or hydraulic devices. Actuators then move the appropriate control surfaces to the desired direction. Today's sensors, actuators and the pilot are part of an electronically controlled system or fly-by-wire (FBW) system that enables full-time surface control utilizing advanced control laws. Control commands from the pilot or autopilot are adjusted to improve the stability characteristics of the airplane.

When the time scale of aircraft dynamics is too small that the airplane can be manually managed or when the pilot workload is demanding, it is necessary to have automatic flight control implemented. The automatic flight control system (AFCS) has two separate control subsystems. One subsystem is required for guiding the vehicle's center of mass along a specific trajectory and the other for controlling the aircraft attitude by rotating it around its center of mass. The first control subsystem type is known as the autopilot. The second control subsystem type is known as the stability augmentation system (SAS) and control augmentation system (CAS).

Autopilots are usually segregated into a lateral and a vertical mode. Typical autopilots in lateral mode are: roll angle hold, turn coordination and heading hold/ VOR hold and in vertical mode: pitch attitude hold, altitude hold, speed/Mach hold and automatic landing. Typical CAS functions are: roll rate, pitch rate, normal acceleration and lateral/directional control. SAS serves as a roll, pitch and yaw damper.

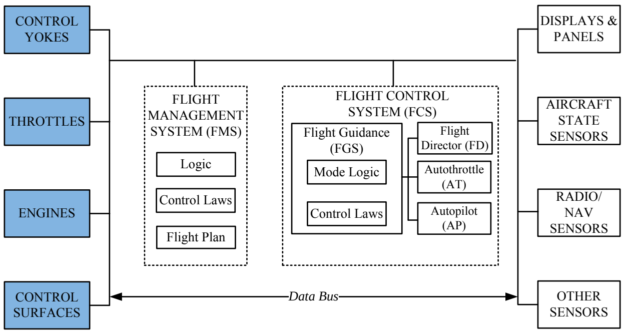

Fig. 3. High level avionics architecture in modern airliners and business jet airplanes [25]

Modern avionics architecture is comprised of many individual systems. Two key functions are the Flight Management System (FMS) and FCS. The FCS is composed of a Flight Guidance System (FGS), Flight Director (FD), Autothrottle (AT) and Auto-Pilot (AP). The FGS is a software function that generates roll and pitch values, and also speed commands used to control the aircraft.

III. AIRCRAFT DISTRIBUTED CONTROL SYSTEMS

Decentralized/distributed control has been a control approach of choice for designing large scale systems for decades. Decentralization assumes splitting the unmanageable complex problems into manageable smaller sub problems, so that the resulting solutions solve the original overall problem.

A. State of the Art in current aircraft distributed control systems

Continuously increasing requirements for aircraft and air transport safety along with operational demands for reliability, performance, efficiency and costs, are shifting the focus of recent development to distributed systems. The massive voting architecture proposed by Airbus [4] suggests to allocate the task of control laws and logic between flight control computers and control surface actuator nodes as shown in Fig. 5. Flight control computers and actuator nodes are connected via an advanced data communication network developed by Airbus. Flight control computers calculate the control laws and proprietary commands for control surface actuator nodes, which are then broadcast as messages over the communication bus. Actuator nodes are equipped with flight control remote modules, and perform massive voting upon receiving the messages from many flight control computers. The massive voting architecture resides upon digital communication technologies. New smart actuator technologies are explored for particular system application. Fault handling in the system proposed from Airbus is resolved within the actuator nodes. A high degree of fault detection as well as a fault location is demonstrated, both due to the large number of nodes [5].

A distributed FCS architecture is presented also for accessing fault handling and redundancy managing on the JAS39 Gripen [6]. The proposed system included 16 nodes. Various simulations showed that distributed sensor nodes meet fault detection coverage of 99% for both transient and permanent faults. The proposed system used a triggered multi master broadcast bus with Time division multiple access communication. As a result, the failure on any node cannot jeopardize communication by sending data outside the dedicated time slot, resulting in a fail silent system.

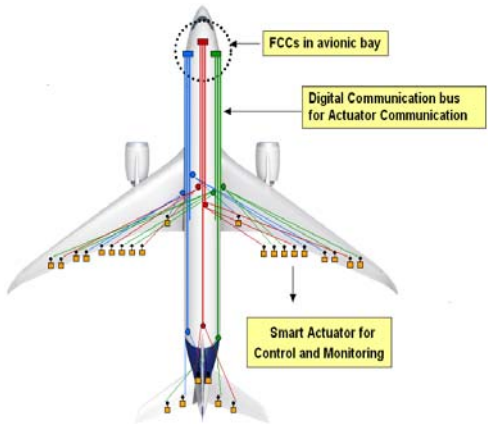

Fig. 4. Fully distributed FCS architecture [5]

Power line communications (PLC) have been proposed for distributed aircraft control systems in [7]. The PLC communications approach eliminates the need for digital data bus wiring by modulating the data on power cables that are installed between the flight control computer and control surface actuators.

Although technology is promising and widely used in other applications, vehicular control systems are not usually installed with PLC systems. For aircraft's FCS, there are many requirements that make implementation of PLC difficult, such as using negative return wires on the power bus instead of chassis return as usual. The problem arises from selective frequency fading or multipath fading. Furthermore, as a general system design safety rule requires, primary and secondary flight surfaces must remain independent. More than one network must be used to reduce wiring, and also for tail surface reliability. Communication speed requirements for various standards must be met, and also to ensure reliability with a given number of remote units. From many other aspects, PLC has to be further developed for aircraft use and its usability is yet to be explored.

Decentralisation is entering other aircraft subsystems, with the development of larger and more complex aircraft. Smart components are proposed for a decentralised fuel management system [8] and microcontrollers are embedded in the pumps, valves and sensors (Fig. 5).

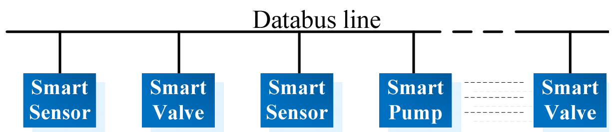

Fig. 5. Architecture of the distributed fuel control system

Proposed system components make its own decisions during various fuel operations, depending on the performed action. They share a time-triggered bus for communication. When a smart component reaches a decision, it transmits it over the bus. For safety, all system components retain a copy of the state vector that describes the system state. Laboratory and real scale testing have been performed proving such a distribution is possible and that the new system can be adaptable to faults.

B. Challenges of distributed system design

In order to create a control system, the control system designer first has to establish the structure of the whole system, its subsystems and their interconnections. Then control inputs and measured outputs are determined. Local controllers are designed using available input and outputs to satisfy the overall system stability and performance. Described procedure is known as decentralized control design.

Properties characterizing complex dynamical systems are: a large scale of system equations, different types of uncertainties of system models, information structure limitations, and communication delays [9]. The problem of high dimensionality can be solved by decomposing the system into subsystems with their respective interconnections. A complex system can be decomposed in two ways. One way is to physically decompose the system according to its physical properties. That can be challenging as there are many systems where it is difficult to identify weak couplings. The other approach is a numerical decomposition of the system. It effectively addresses the problem of high dimensionality [9].

Control of large scale complex systems requires efficient design methods and algorithms whose implementation needs minimal information exchange among local systems [9]. Recent growth of communication networks intensifies the move of traditional system theory to communication networks. This is particularly suitable for complex real world systems such as transportation and large manufacturing systems, the internet or embedded control systems. Wireless networks offer significant advantages but also introduce some drawbacks compared with wired networks. The advantages include low cost of operation, ease of installation and reconfiguration, natural reliability, robustness, and adaptability enabling in avionics a flight-by-wireless system [10]. Drawbacks are time delays, packet loss, finite capacity, and data flow problems.

Digital networked dynamic system design can be analysed from the position of:

- Control over a network covers the design of feedback strategies adapted to existing control systems where control is performed via unreliable communication links;
- Control of networks that is concerned with providing a defined level of performance to network data flow;
- Multi agent systems study how network architecture and interactions between different network components affects global control goals.

Interconnected systems have been classified according to different principles and system structures into disjoint, overlapping and hierarchical decompositions, as well as decompositions for time scale, singular symmetric systems [9]. A basic modern theory problem in interconnected systems is the approach to timing. The timing problem is in finding the communication frequency of the networked-based feedback loops for which system stability and performance is satisfied. Typical phenomena concerning network performance are: random delays, packet dropouts, quantization and data rate limits.

We can separate time driven and event driven feedback schemes, regarding to the data transmission approach. The periodic sampling of the continuous time system characterizes the time driven approach. This approach generates redundant communication within the feedback loop. That results in an effort to reduce the communication traffic only to necessary data. The event driven system communication is triggered by the occurrence of an event to engage a sample realization. As a result, the event triggered control relieves the communication network and also saves energy.

IV. Emerging technologies related to flight control systems

A. MEMS based FCS

The MEMS is a "batch-fabricated integrated microscale system that; converts physical stimuli, events, and parameters to electrical, mechanical and optical signals and vice versa; performs actuation, sensing and other functions; comprises control, diagnostics, signal processing and data acquisition features" [11] .

MEMS sensors are very promising in aerospace technology because of their small size (the overall dimensions are a few millimetres), low power consumption (fractions of a watt), high reliability (operation life up to 120000 h) and extremely low cost [12]. Although MEMS sensors lack the accuracy of conventional sensors, it is being improved continuously. For example, the drift of the first MEMS gyros put into mass production in 1995 was greater than 500 deg/h according to [12]. Currently, it is reduced to below 1.0 deg/h [13], and it is predicted to go down to 0.1 deg/h [12].

Large manufacturers are developing MEMS based gyros for production to replace a low and medium accuracy laser and fiber optic gyros. For example, the company Northrop Grumman LITEF GmbH is producing a small sized inertial reference system LCR110 with MEMS accelerometers for civil aviation purposes. Current development lies in bringing the performance of mass produced MEMS sensors to a level required for use in aircraft navigation systems, and in designing MEMS based devices for a wide range of aircraft. MEMS sensors are known to feature zero bias and scale factor depending on temperature, gyro output depending on linear overloads, high noise components, and sensor output parameters practically linearly related to power supply instability. Performance improvements are based on a number of circuit, software, and design modifications.

MEMS sensors are particularly important for the development of UAV flight control systems. The flight control system enables an UAV to fly autonomously based on a series of preplanned waypoints while transferring real-time data of mission targets to ground control stations. Commercial UAV flight control systems are available by companies like MicroPilot and UAV Flight Systems.

UAV flight control systems must provide at least altitude hold control and global positioning system navigation, in order to perform UAV missions. Using several UAV agents to perform a mission quickly and more efficiently as a team is a problem of distributed control of UAV swarms.

B. UAV swarms

UAV are a rapidly evolving technology with a variety of military applications such as reconnaissance, target and decoy combat missions [14]. A variety of civil and commercial applications can be performed also. Certain surveillance applications such search and rescue can be accomplished most effectively by teams of cooperating autonomous agents, i.e. swarms of UAVs.

Development of reliable autonomous navigation algorithms for individual UAVs was a technological prerequisite for development of cooperative team technologies and frameworks. Recently explored approaches that deal with multi-agent collaboration significantly rely on agent-to-agent communication. Ad-hoc wireless technologies are explored for line of sight communications, primarily due to the availability of low cost of the shelf technologies/parts [15]. Using the communication infrastructure, a team of UAVs receives a list of mission tasks and collaborates to autonomously and efficiently assign the tasks among themselves.

Multi-level control systems are designed for centralized mission command centres. Levels for mission control, agents monitoring and task execution monitoring comprise mission command center control. Such an approach reduces the amount of training for the mission operator, relieving him of monitoring and task organizing duties.

Completely decentralized and autonomous system enables the fleet of UAVs to accomplish missions beyond the range of any centralized command station [16]. Agents within such a system are performing all of the collaboration and control processing on the aircraft. Also they perform decentralized task allocation for a dynamic mission via on-board computation and ad-hoc aircraft-to-aircraft communication.

Determining the stability properties of multi-agent teams is rather challenging, but can be verified in restricted scenarios. This problem is addressed using methods such as model predictive control [17] and receding horizon control [18]. Future work includes development of platforms with described properties within larger airframe UAVs, all in an effort to increase flight time and support more complicated missions [19].

C. Fault Detection and Isolation

According to [20], a fault is „an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition“ and a failure is “a permanent interruption of a system’s ability to perform a required function under specified operating conditions”. Large distributed systems like automotive systems, jet engine control, and teams of unmanned vehicles are comprised of many individual components and sensors. It is very difficult to diagnose faults in interconnected distributed systems using a centralized FDI architecture, mostly due to constraints imposed by computational abilities and communication limitations. Therefore, a distributed FDI architecture is developed extensively in recent years by [21] and [22].

Operations of distributed systems rely significantly on sensory health. A sensor fault may lead to poor control performance and compromise stability of the control system. Sensor information error can propagate to other subsystems trough interconnections, affecting their performance, and also causing difficulties pinpointing and isolating the faulty unit. Therefore, sensor fault diagnosis is a critical issue in distributed interconnected control systems. “A fault-tolerant control system is capable of controlling the system with satisfactory performance even if one or several faults, or more critically, one or several failures occur in this system” [23].

Distributed FDI architecture is proposed by [21]. For each subsystem a local FDI component is designed. The FDI component uses local measurements and communicated information from neighbouring FDI components associated by interconnection. Each local FDI component consists of a fault detector estimator and adaptive fault isolation estimator. Fault detector estimator monitors the local subsystem under normal operating conditions. If a sensor fault is detected, fault isolation estimator isolates subsystem where the fault has occurred. There is an inherent trade-off between robustness and fault detectability. The importance of adaptive thresholds for distributed sensor FDI is demonstrated, as they ensure robustness with respect to interactions among interconnected subsystems and modelling uncertainty.

D. Distributed optimisation

Aerospace systems control can be described as a complex problem. Approaches from computer science are introduced to aerospace systems in order to cope with the large complexity of such systems. One of such approaches is reinforcement learning which is based on selecting actions, receiving rewards, and updating settings for future actions.

Another promising approach for distributed aerospace systems is the Collective Intelligence (COIN) framework [24]. Collective in this case is “a system of adaptive computational agents with a specified system level performance criterion” [24]. COIN techniques have already been applied to a many of distributed optimization problems such as network routing and data collection by autonomous vehicles. Collective systems address the optimization task as tasks distributed among agents which represent system variables. The variables can represent a specific control surface position on an aircraft. The collective’s solution is generated when agents select actions and receive rewards depending on the system objective. The actions can be commands relayed to a control system. Equilibrium for the multi agent system is reached when the agents can no longer improve their rewards by selecting a different choice of actions. The COIN research puts a focus on local reward functions which are also referred to as private utilities, as the connection to the increase of the convergence rate is clearly proven [24]. Probability Collectives (PC) theory extends the COIN framework and handles constraints more explicitly as it is necessary for aerospace systems. PC theory concentrates on how the system agents update the probability distributions on range of their possible actions instead of focusing on the joint action created by sampling those distributions.

The collectives approach is specifically designed for systems that are distributed. The use of probabilities removes any issues associated with discrete actuation. Because noise and disturbance are often characterized using probabilities, the collectives approach is naturally suited. Collectives can use locally available information, or alternatively include information from other agents and can use a data broadcast from a centralized source. Formulating the problem of control as a distributed optimization problem makes these systems benefit from the application of machine learning algorithms, statistics, gradient-based methods for optimization, and game theory strategies [24].

V. CONCLUSION

Distributed FCSs present a significant leap in the evolution of aircraft FCS architectures. Novel technological advances in areas of embedded computing and communication, machine learning, and multi agent systems control continue to push FCS design towards distributed systems. Although there are some demonstrations of distributed systems for aircrafts, they are mostly analysed from the aspect of fault detectability and identification. However, distributed control systems should be further explored to find the final optimal way how the control law calculation can be decentralised at the same time fulfilling all safety criteria. For example, some systems offer voting mechanisms for identical flight control computers and nodes, to achieve redundancy.

Authors of this review conclude that other ways of decentralisation, possibly across hardware architecture boundaries between different control surfaces should be investigated, and that the possibility of decentralised decision making needs to be further examined.

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