University of Zagreb
Faculty of Transport and Traffic Sciences

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Programming period 2015 – 2017

Proceedings of the technical reports

Zagreb, 2017

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FOREWORD

Science and research in all areas is oriented towards research groups and networks. Education, research and innovation are characterised by a strong flow of knowledge, introduction of research results and innovation practice into education, strong partnerships and intellectual property management. New ideas and knowledge, new processes, products and services, and new entrepreneurship are the ingredients of investigative creativity. In the service of a research-oriented university, the Faculty of Transport and Traffic Sciences intends to take special care of its students as potential researchers. This is especially important for postgraduate students who should have the opportunity to do research as a part of a project. However, research should be equally introduced at the graduate level where learning should be oriented towards research (as a function of the paradigm shift from learning after research to learning through research).

Faculty of Transport and Traffic Sciences established in 2014 a strategic framework in order to improve the quality of research activities and increase productivity in the field of traffic and transportation engineering. The purpose of the strategic framework is to create all necessary conditions for the development of the knowledge triangle at the Faculty, according to the following goals: establish a system for active participation in collection, processing, interpretation and publication of statistical and other indicators of research, development and innovation; encourage and evaluate the work of researchers and the establishment of research groups; encourage cooperation in research, development and innovation; develop e-infrastructure in order to facilitate research and education activity; plan research investments, and active participation in smart specialisation processes.

Critical segment of the framework is the Program for stimulation of research and innovation at the Faculty of Transport and Traffic Sciences. The goal of the Program is to encourage the development and innovative character of scientific activities at the Faculty. The program's emphasis on the outcomes of scientific research (impact of scientific activities on certain segments of society and the economy), and the outputs in the form of research results.

After only two years of active implementation of the Program, it is our pleasure that we can present general results from Faculty's research groups in forms of technical reports in this proceedings.

Faculty will continue to encourage the development and innovative character of scientific activities, with emphasis on the outcomes it terms of impact of scientific activities on specific segments of transport and traffic.

Assoc. Prof. Doris Novak
Chairman of Committee on Science and Projects
Faculty of Transport and Traffic Sciences

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DISTRIBUTED FLIGHT CONTROL SYSTEM SIMULATOR FOR AIRCRAFT AUTOSTABILIZATION

ABSTRACT

The current automatic aircraft control concept includes a central system of computers that controls the servo-actuators located near the flight control surfaces. The main point of this project is to decentralize the flight control system in a way to locate the microprocessors near the flight control surfaces that would enable reduction of mass and simplification of the control system and architecture. The work done so far is combination of theoretical and experimental research. The first results are published as conference papers indexed in IEEE Explore and Scopus database. The first paper was aimed to provide a survey of technologies developed and deployed for distributed flight control system, while the second one outlines design for Fully Distributed Flight Control System (FDFCS) and its control units, identifies the possible problems that a distributed flight control system implies and solves, and sets requirements for the planned FDFCS Hardware in the Loop Simulator.

KEYWORDS:

Distributed control system, aircraft control, Federated Architecture; Integrated Modular Architecture, fault tolerance

1. 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 the subject of our research project. 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 significant amount of data processing is done in local embedded controllers and the master control unit has a global overview of the whole system.

This project is continuation of written project proposal for funding from the EU structural fund at the end of 2014 within the tender “Research scholarships for professional development of young researchers and postdoctoral fellows”. The research team started to collaborate during writing of the mentioned project proposal. This collaboration resulted in a scientific review article: “Technologies for Distributed Flight Control Systems: a Review”, presented at IEEE MIPRO conference in May 2015 [1].

This report is organized as follows. The research goal and motivation of the project is described in Section 2. Section 3 overviews the project research activities. An overview of the budget spent including a short description of the purchased equipment is given in Section 4. Section 5 shows the project results with emphasis on applications for new projects, obtained projects and grants, and published papers. Report ends with a conclusion and future work sections.

2. RESEARCH GOAL AND MOTIVATION

Flight control system (FCS) consists of flight control surfaces, cockpit controls and connecting linkages. Fly-by-wire (FBW) FCS 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.

There are three possible types of system architectures for a control system in general: (i) Centralized architecture; (ii) Distributed architecture; and (iii) Federated architecture. A centralized 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 [2]. In addition, 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 applied smart sensors and the results are transmitted. A central control unit does not exist and all subsystems have to communicate with each other [2]. The federated architecture is a compromise between the centralized 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 [2].

A centralized control approach for a FCS requires a large amount of electrical cables originating at the flight control computer and ending at actuators and control surfaces in one case, and originating in sensors and the flight computer in the other case. 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.

The goal of our research is to develop concepts and control algorithms for a distributed FCS. The emphasis is on implementation of a simulator for distributed FCS and associated control hardware in the loop. The main idea is to decentralize the FCS by putting the control system units near the control surfaces. The benefits of such FCS are: less wiring for transferring the signals, faster response time and greater robustness.

3. RESEARCH ACTIVITIES

This section is describing the research activities done by the project team members during the project. The planned activities are divided among team members and include theoretical and experimental parts.

3.1 Review of current research in the field of distributed FCS

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 [3] suggests to allocate the task of control laws and logic between flight control computers and control surface actuator nodes as shown in **Error! Reference source not found.** 1. Flight control computers and actuator nodes are connected via an advanced data communication network developed by Airbus. Flight control computers execute 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 fault location is demonstrated, both due to the large number of nodes [4].

A distributed FCS architecture is presented also for accessing fault handling and redundancy managing on the military aircraft JAS39 Gripen [5]. 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 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.

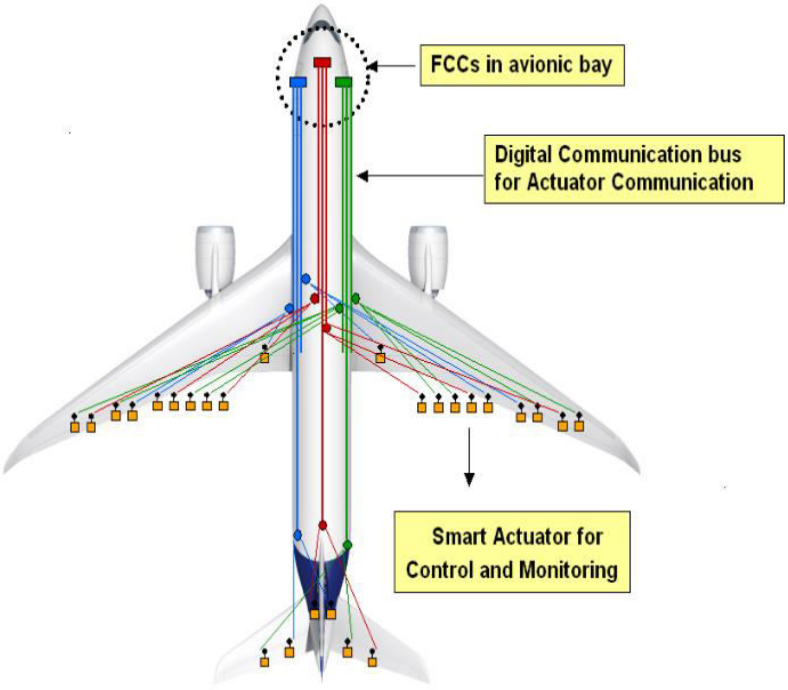

Figure 1 – Fully distributed FCS architecture [4]

Power line communications (PLC) have been proposed for distributed aircraft control systems in [6]. The PLC communications approach eliminates the need for a 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 that primary and secondary flight surfaces must remain independent. More than one network must be used to reduce wiring and for tail surface reliability also. Communication speed requirements for various standards must be met, and to ensure reliability with a given number of remote units also. 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 [7] and microcontrollers are embedded in the pumps, valves and sensors (**Error! Reference source not found.**).

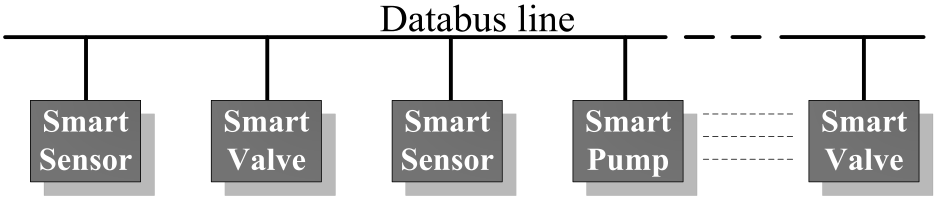

Figure 2 – Architecture of a distributed fuel control system

Proposed system components make their 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 that such a distribution is possible and that the new system can be adaptable to faults.

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 aircraft, 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 execution of the control law 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.

The authors 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.

3.2 Proposed design of Central Units for FDFCS

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 Fully Distributed Flight Control System (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 the 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 Figure 3.

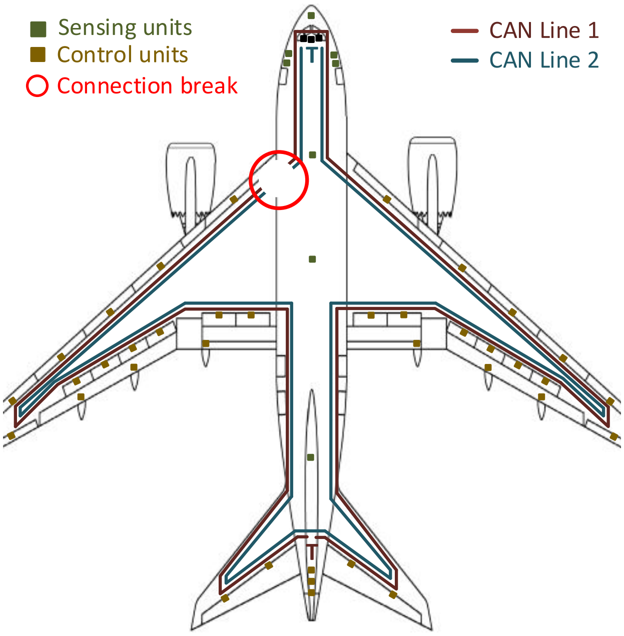

Figure 3 – FDFCS CAN network routing with separate termination points for case of connection break near left wing root

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 power provided by both units, 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.

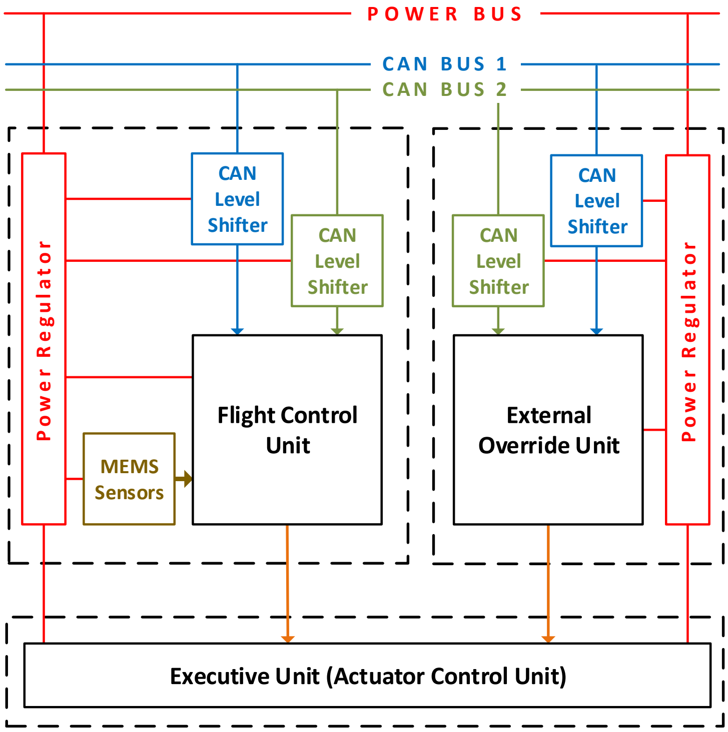

Figure 4 – Proposed CU design for FDFCS

Microelectromechanical systems (MEMS) based sensors are also an option but 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, 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 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 the 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. 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 [5].

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, degraded mode of operation should be available. The degraded control mode must allow direct control of minimal necessary units. Direct control should transfer pilot commands to the control surfaces without any interference. Under no circumstances like other systems failure or corruption, should the 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.

3.3 Hardware in the Loop Simulator

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. Therefore, a dedicated HIL simulator will be built to answer these open questions and estimate the benefits and disadvantages of the proposed architecture. In order to make such a simulation certain requirements have to be fulfilled. The proposed HIL schema for FDFCS is shown in Figure 5. 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 framework 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.

The embedded CUs will be designed so they will be able to run the FCS. CUs will be executing control laws necessary to control the simulated aircraft control surface actuators. Needed data from aircraft sensors like the air data unit, inertial reference unit, and GPS receiver will be simulated in Matlab/Simulink to ensure needed realistic sensor measurements. The dynamics of the actuators controlled by CUs, will also be emulated in Matlab/Simulink. 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.

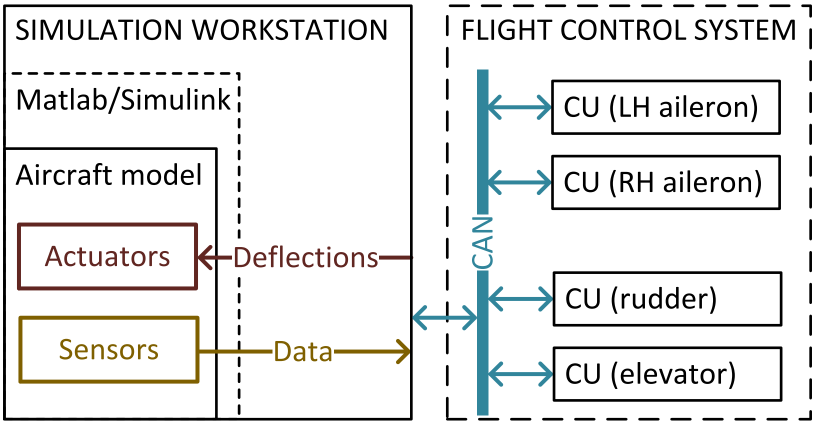

Figure 5 – Proposed HIL schema for FDFCS

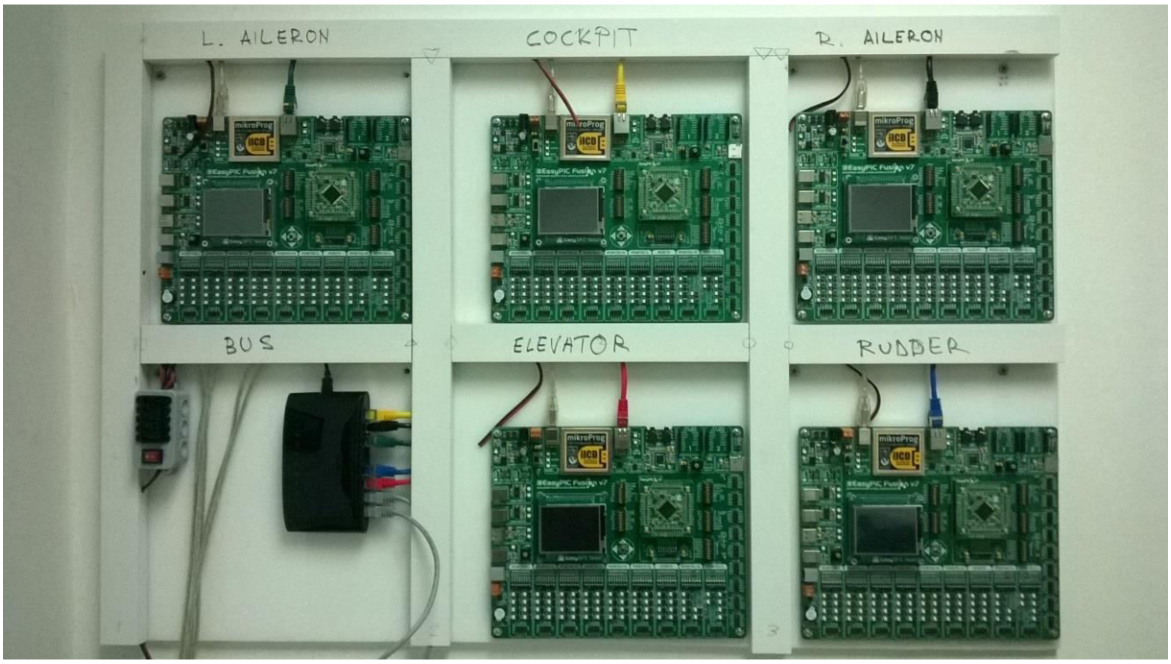

Figure 6 – CUs that will be used in the HIL simulator

4. BUDGET SPENDING

The approved budget for the project per year was 15,000.00 HRK, cumulatively 30,000.00 HRK. The first year budget was spent for equipment necessary for building a HIL simulator, conference paper presentation and an e-course for EU project management. The total spent amount was 15,140.00 HRK. The second year approved budget was also 15,000.00 HRK. Some of the funds for the second year of the project (2,442.16 HRK) have been spent for attending the MIPRO 2016 conference to pay the conference fee and travel expenses. The rest of the funds will be used for buying of a work-station and subscription on two leading journals in the field of aircraft flight control as listed in table 1.

Table 1 – Planned and realized activities with budget overview.

Nr.	**Planned activity**	**Planned budget**	**Achieved**	**Cost**
1.	Essential equipment purchase	11,300.00 HRK	Bought 1 ATX power supply, S-FTP cable, 5 development boards EasyPic Fusion v7	11,129.50 HRK
2.	Research dissemination (1st year)	3,270.00 HRK	1 x registration fee for the conference MIPRO 2015	1,511.75 HRK
3.	Professional education	5,000.00 HRK	Completed E-course for EU funds project management	2,499.00 HRK
4.	Research and experimental work (1st year)	0.00 HRK	Written two scientific conference papers and mounted development boards	0.00 HRK
5.	Advisory services	10,000.00 HRK	No (insufficient funds)	0.00 HRK
6.	Research dissemination (2nd year)	11,700.00 HRK	1 x registration fee + travel expenses for the conference MIPRO 2016	2,442.16 HRK
7.	Purchase of additional equipment and servers to simulate the flight of aircraft in real time	4,000.00 HRK	1 x workstation	10,675.94 HRK
8.	Research and experimental work; writing project applications	0.00 HRK	Membership fee and subscriptions to the Journals Guidance, Control and Dynamics and Journal of Aircraft	1,881.90 HRK
9.	Short Term Mobility	9,500.00 HRK	No (insufficient funds)	0.00 HRK
10.	Attending Transport Research Arena Conference in Warsaw, April 2016.	6,500.00 HRK	No (insufficient funds)	0.00 HRK

5. RESULTS

This section is describing the results achieved during the two project years. The results are divided into five subsections related to involvement of students (including PhD students), cooperation with industry and academia (domestic and foreign), submitted project applications, obtained additional project and funds, and finished with a list of published papers. The list of published papers contains a very short paper description.

5.1 Involvement of students

The research member of our team Miroslav Šegvić is also a PhD candidate at Faculty of Transport and Traffic Sciences. His research field is flight control and dynamics. Through this project, Miroslav Šegvić profiled himself on the experimental flight control system research. He used the experience gathered on the research topics, that were facilitated by this project, to write the two scientific papers that were presented on the international conference MIPRO.

5.2. Cooperation with industry and academia

Regarding cooperation with industry and academia, our team made an initial contact with Prof. Ruxandra Botez from Laboratory in AeroServoElasticity, Active Control and Avionics, University of Quebec in Canada. Prof. Botez invited us for a visit to the aforementioned Laboratory. The leader of this research team, Karolina Krajček Nikolić applied twice for a short visit grant schema funded by University of Zagreb, but without success. Due to lack of funds, this activity was not realized. Industry cooperation is established with company Croatia Airlines (CA) since our research team member Miroslav Šegvić is working in CA as an engineer. This working place gives him first row insights into problems related to control of commercial aircrafts.

5.3. Project applications

In table 2 all submitted project proposals that got rejected or are currently in review are listed. The project proposals are result of participation of the research team member Edouard Ivanjko in the EU COST action TU1102 Towards Autonomic Road Transport Support Systems. To increase the probability of obtaining new funding the leader of this research team, Karolina Krajček Nikolić participated the workshops "Kako napisati uspješnu projektnu prijavu za individualnu stipendiju u okviru Marie Sklodowska - Curie akcija" during June 2015 and "Od neuspješnih projekata do dodjele bespovratnih sredstava" during November 2015. The first workshop was organized by the Agency for mobility and EU programs, and the second by WYG International.

Table 2 – Overview of submitted project proposals.

Nr.	Funding scheme	Project name	Budget	Status
1.	HORIZON2020	Eliminating air QUality problems using an Autonomic Layer In the Smart city Environment EQUALISE	6,580,578.75 EUR	Rejected
2.	HORIZON2020	COLlective TRAnsport/TRAvel INtelligence COLTRAIN	3,440,000.00 EUR	Rejected
3.	HRZZ	Optimization of Routes for Electric Delivery Vehicles OpRED	702,000.00 HRK	Rejected
4.	PoC BICRO	Advanced traffic counter based on multispectral video	260,000.00 HRK	Rejected
5.	COST	OC-2016-1-20366 "Cooperative intelligent systems for transport "	Yearly defined	Rejected
6.	COST	OC-2016-2-21618 " Intelligent Mobility Pan European Skills Network "	Yearly defined	In review
8.	Financing scientific centres of excellence in Croatia	Scientific centre of excellence for data science and cooperative systems	5,000,000.00 EUR	In review

5.4 Obtained additional projects and funds

Description of accepted project proposals and other funds received are given in Table 3. Obtained funds enabled networking with foreign researchers and access to future summer schools.

5.5. Published papers

The results of our research are published in papers two papers ([1] and [10]) indexed in IEEE Explore and Scopus database. Both papers are scientific conference papers for the MIPRO international symposium in 2015 and 2016. The first paper reviews the state of the art (SOTA) in distributed flight control technologies using publicly available, scientific and technical publications. 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 system and technologies are represented with examples of real systems including swarms of small Unmanned Aerial Vehicles and distributed networks for Fault Detection and Isolation.

The second paper outlines design and requirements for planned FDFCS HIL simulator and its Control Units (CU). Main contribution is that aircraft stability and trajectory control logic is distributed to a network of independent CUs collocated on actuators collaborating to control the aircraft with respect to common goal. The paper also identifies the problems that a distributed FCS implies and solves.

Table 3 – Overview of submitted project proposals.

Nr.	Funding scheme	Name of project or grant	Short description	Budget
1.	EU JCR	Road-transport & Emissions Modelling (REM) workshop	Networking event and workshop regarding modelling and simulation od road vehicles emissions. Held in Skopje, Macedonia and Edouard Ivanjko participated.	700.00 EUR
2.	Scientific centres of excellence	Scientific centre of excellence for data science and cooperative systems	Research and collaboration project related to establishing a scientific centre of excellence in data science and advanced cooperative systems. Project associate Edouard Ivanjko is member of the research unit related to data science.	Yearly 550,000.00 HRK
3.	ERASMUSplus	Teaching visit to the Department for traffic and transport Faculty of Technical Sciences St Kliment Ohridski University, Bitola, Macedonia	Grant holder is Edouard Ivanjko. Aim of the visit is to teach the foreign students to new developments in application of artificial intelligence in road traffic control and how to simulate such systems using VISSM, EnViVeR and Matlab. Additionally, existing research cooperation will be extended.	1,000.00 EUR
4.	COST	IC1406 High-Performance Modelling and Simulation for Big Data Applications (cHiPSet)	Researcher Edouard Ivanjko is management committee member for Croatia. Hi is also member of the traffic group of the application workpackage.	Yearly defined for networking meetings
5.	University of Zagreb	Development of Measurement Systems in the Low Speed Wind Tunnel	The grant holder is Anita Domitrović. Karolina Krajček Nikolić is a research team member. Aim of the project is to equip the Aerodynamic Laboratory with basic measuring systems.	22,079.63 HRK
6.	University of Zagreb	Route optimization for small electric vehicles with the criteria of minimal consumption	The aim of the project is to develop a method of collecting data of the energy consumption of electric vehicles and construct electronic circuit for measuring necessary parameters of electric vehicle.	3,121.67 EUR

6. CONCLUSION AND FUTURE WORK

The primary goal of the project was to set a starting point for the research of experimental flight control systems. That included the research of the state of the art and academic focus on the research area. After that, a proposal for an experimental flight control system followed. Research equipment for HIL simulation was pre-set. All the goals from this project were completed and make a solid base for planned future work. The future work will include development of the software for the distributed flight control system. Build simulation setup will allow an analysis of the proposed distributed system and comparison with classic centralised control system. The exploration of the characteristics of the proposed control concept and practicality for the application in the aviation vehicles will be the topic of future scientific papers.

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