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COMPLEX POWER PLANT CONTROL & MONITORING SYSTEMS FOR SMALL UTILITY AIRCRAFT AND MODERN TRENDS IN ACTUATION

Given article describes the motivation for use of Commercial Off the Shelf (COTS) components for the development of critical control applications in the aerospace industry. A V-cycle model based development is introduced and its advantages and development practices that leads from design of a MATLAB/Simulink models into a real target application are depicted. Attention is also paid on FAA/EASA certification authorities requirements ([6, 7, 8]) with respect to a certification process of any newly developed aviation equipment. These practices are being used during the development of a Complex Power-plant Control System for a small civil aircraft, which function and individual subparts are also described. Model based development of the Complex Power-plant Control System is described and simulation results are given.

Key words: *smart actuation, EHA/EMA actuator, distributed control systems, BLDC motor modelling.*

Introduction

The aerospace industry is well known for its strong requirements on safety, reliability and guarantee of long lasting airworthiness. Use of COTS components and development tools is even more complicated because of sector rigidity and sticking to long term and examined standards, which frequently do not reflect recent developments and market requirements. Prior being accepted, every COTS based component or embedded system must be analyzed, tested and its performance, fault tolerance and electromagnetic compatibility has to be proven.

COTS components were firstly adopted by the industrial and automotive sector. Long term experience in these two industries has proved that COTS components are comparable with custom designed components in terms of efficiency, performance and reliability. In addition, COTS components and development tools are often much cheaper and available in different variants from several vendors which makes development much flexible.

Utilization of COTS components also brings many advantages that result from implementation of advanced technology, like COTS real-time operating systems (RTOS), industrial data buses (CAN bus, CANAerospace Higher Layer Protocol for communication [1], [3], Time Triggered Protocol / TTP [2]) and development tools. These technologies are maintained by commercial vendors and tested by wide spectra of users. Using these tested and specialized COTS components and development tools may rapidly speed up the development cycle, thus considerably save the development costs. Some of them are supported by certification authorities (FAA, [4]) and were accepted as technical standards [5].

1. Development of Complex Power-plant Control System

One of the major parts of UNIS' research activities within the scope of the CESAR project (an integrated project of the 6th framework programme of the EU) is the development of a Complex Power-plant Control System (CP-CS) for civil aircraft category FAR23/CS-23 with a twin turboprop engine.

The development of CP-CS is based on the above stated development techniques and certification requirements. The CP-CS is an engine control system with an advanced control architecture, which has to be more complex compared to the present ones. An intelligent power-plant control system should enable to overcome current limitations and achieve improved performance, capability, reliability and safety while maintaining affordable costs. Approaches to achieving these objectives include simplification of aircraft control, prolongation of engine lifetime and fault detection in association with adaptation of new control algorithms.

CP-CS is designed as a distributed control system with benefits in open architecture, reduced size and weight. Open architecture enables implementation of intelligent subsystems that communicate via a standardized protocol over a communication data bus. Overall reliability and safety is assured by a two-channel system redundancy.

1.1 CP-CS architecture

At the distributed engine control architecture any number of control elements are interconnected via a common, standardized communication interface. Sensors and actuators are replaced by control nodes, which may provide sensor data, operate actuators or perform combination of both. Wiring harness weight is replaced by a simple, but robust communication lines. Reduction of weight is primary goal but the standardized interface is also an enabling feature, which is necessary for effective implementation of future adaptive control applications.

Nodes in distributed control system architecture are equipped with a certain degree of ”intelligence”. Sensor nodes provide information about the physical state of the engine using a predefined data structure. This could take the form of in-line ranked data in engineering units or a processed state of an engine function. Actuator nodes receive commands and data from the electronic control unit to operate the actuator at its most efficient operation. Distributed engine control architecture is shown in Fig. 1.

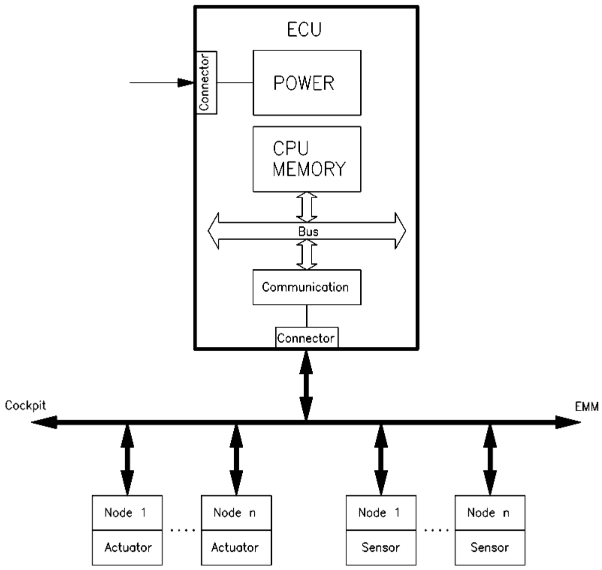

Fig. 1. Distributed control system architecture

The engine control system is significantly reduced in size and weight and the open communication architecture enables simplified expansion. Since the communication network is standardized, there is no need for unique interface and signal conditioning circuitry for each control element. The number of conductors in wiring harness and the connectors do not determine the system design and electronic package configuration. The location of the ECU is not critical allowing the electronic hardware to be relocated in a more kindly environment. This leads to a broad cross platform standardization and significant cost reduction in both acquisition and maintenance.

The standardized open network communication architecture also does not constrain the function of the control elements. Intelligent nested sub-loops enable the implementation of advanced adaptive control subsystems, which may operate at significantly higher internal data rates.

The CP-CS is designed to be fully digital and redundant, which means that engine is controlled by a Full authority digital engine control (FADEC) device with a two channel redundancy. Each channel is connected to the same or redundancy peripherals. The secondary channel monitors the primary channel, respectively the primary channel monitors the secondary one. Each channel of the redundancy control system can replace the function of the other channel. In the event of the erroneous behaviour, the error message is sent to the cockpit.

General CP-CS architecture and interconnections among individual subsystems is shown in Fig. 2.

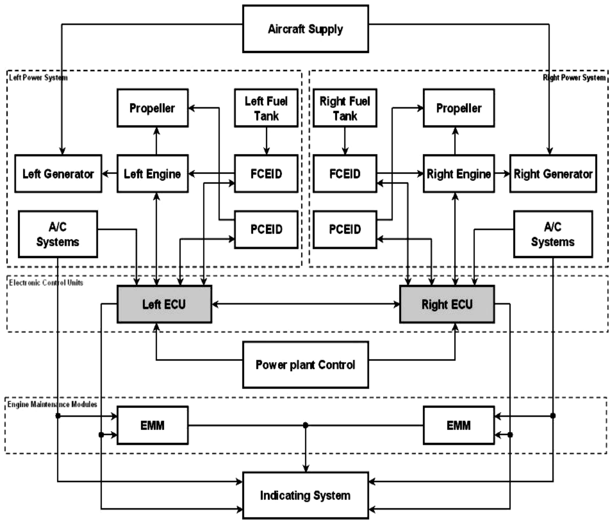

Fig. 2. General CP-CS architecture

A short description of individual subsystems which create the CP-CS is given in the next list:

FCEID (Fuel Control Electrical Interface Device) – is a block that represents fuel pump control and regulation system which needs no mechanical drive from engine gearbox. Its operation is fully controlled only by electronic control system, thus meets the philosophy of more electric aircraft.

PCEID (Propeller Control Electrical Interface) – is a block that represents propeller control and regulation system.

EMM (Engine Maintenance Module) – is used as an automatic engine data concentrator and real-time maintenance evaluate equipment. This device is installed on the aircraft and processes automatically all necessary data from the start of the aircraft’s system. All necessary EMM state information is shown in cockpit indicators or multifunctional display.

ECU (Electronic Control Unit) - is an automatic engine control system that shall ensure the engine’s functionality at all operational ratings under expected operational conditions. The ECU uses primary information data acquired from sensors and provides primary control of actuators. The acquired data and ECU state information are available on the A/C data bus.

2. Engine maintenance module

Engine maintenance (inspections, maintenance services and repairs) strongly depends on aircraft category and type, and also on the chosen strategy of operation. It is influenced by design philosophy, selected manufacturing technologies and operating conditions. The CESAR project is focused on small-size commercial twin-engine aircraft powered by small turboprop engines.

Diagnostic systems that are built nowadays for modern but larger engines usually consist of both an airborne and a ground part. The airborne part is intended to collect and monitor critical system failures in real-time for the pilots to take decisive actions in case of a critical failure whereas the ground part aims at post-flight information processing and analysis for systems troubleshooting, early failure detection and correction and long-term prediction.

This project proposes to adapt this concept for small engines based on on-board diagnostic, monitoring and maintenance support systems with a high efficiency and accuracy of fault detection, monitoring and diagnostic for sensors and engine components.

2.1 EMM design concept

The EMM will allow for radical improvement of flight safety and reliability, and simultaneous reduction of maintenance costs. The EMM as a part of CP-CS is an on-board device and is intended mainly for on-board diagnostic, engine data storage and data download for post-flight engine diagnostic and trend monitoring. EMM design concept is shown in Fig. 3.

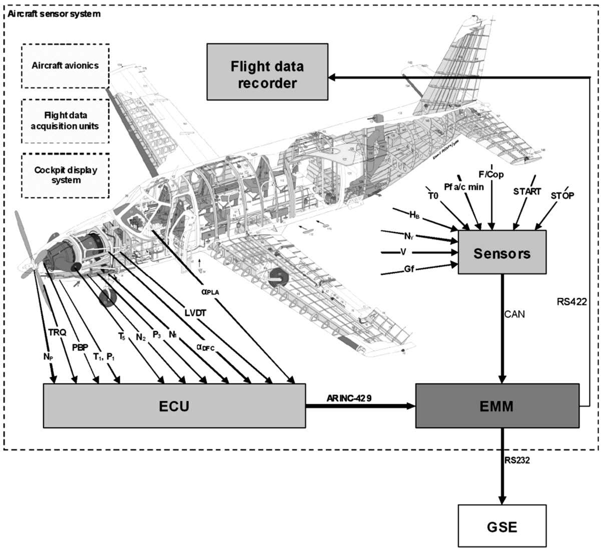

Fig. 3. Design concept of engine monitoring system

It's main characteristics are:

- Mixed signal and data communication links.
- Usage of modern smart and intelligent sensors is available.
- On-board low-cost monitoring system based on modular multi-channel communication databuse.
- Standard multisignal processing unit to process sensor signals and preprocess engine maintenance parameters.
- On board data storage.
- Design based on COTS (Commercial-Off-The-Shelf) components, sensors and data buse.
- Modular and distributed multi-channel communication databuse concept EMM I/ Integrated concept EMM II (for single, twin engine aircraft).
- Built-in test (BIT).
- Cost effective solution.
- Easy HW and SW modifications.

2.2 EMM on-board package

Engine Maintenance Module (EMM) is used as an automatic engine data concentrator and real-time maintenance evaluate equipment. This device is installed on the aircraft and processes automatically all necessary data from the start of the aircraft/s system. All necessary EMM state information is shown in cockpit indicators or multifunctional display.

The EMM processes data acquired from the connected sensors to the SIU or data acquired from the aircraft systems. The data from the aircraft and engine systems are received from the aircraft data bus (ARINC-429, etc). The EMM is fully interchangeable.

The main functions of the engine maintenance module are as follows:

- Acquisition and preliminary processing of analogue and discrete data from engine and aricraft sensors and storage of engine usage parameters for further GSE processing,
- Real-time calculation of corrected values of selected parameters,
- Processing of acquired analogue or discrete signals relating to operational mode of the engine,
- Monitoring and recording of important parameters exceeding limits,
- Fault identification,
- Post fligt protocol creation (consumed and remaining cycles/hours, status, failures, cumulative hours of engine run, cumulative number of starts, parameters exceeding limits during mission, rundown),
- Sending of protocol to CDS and storage in engine history memory, with delivery of the information on the detected failures and faults,
- Sending (on crew request) collected engine data via the Data Transfer Block to the ground maintenance data base (MDB),
- Sending of acquired engine data to the FDAU,
- Built-in test (BIT) of the unit, test of sensors and of the communication channels to the EMM.

2.2.1 EMM core

The EMM Core contains key modules for processing of the acquired data from the connected sensors or data acquired from the aircraft data bus. The data are processed by the algorithms supplied by the engine producer.

The EMM acquires data from sensors, annunciators and aircraft systems with frequency necessary for the correct processing of the all algorithms.

All acquired data are filtered for obtain of the reliable values for evaluation by the EMM algorithms. The filtration procedures have to be consulted with the EMM algorithms producer (engine producer).

The EMM indicates the states of the received and processed values.

2.3 Sensor interface unit

Sensor Interface Unit (SIU) is designed for accepting analogue and discrete input signals from the engine and aircraft. All signals from the active or passive sensors are filtered and converted to their digital representation. Converted data are concentrated in the communication interface and send to the EMM core module for processing and evaluating.

The engine and aircraft wiring and instrumentation have to be consulted and agreed with the engine and aircraft producer. The EMM producer is responsible for accuracy and reliability of the sensing parameters. The engine and aircraft producers are responsible for the installation requirements and maintenance conditions.

2.4 On-ground package

Ground support equipment (GSE) makes accessible the stored data in the EMM memory for the external data processing (data analysis, visualization, etc.). The data from the EMM are available on the GSE communication interface. The device, which can access to the EMM, has to be equipped by the compatible communication interface (USB – Universal Serial Bus). The data can be loaded from the EMM either by the special Service device or by the compatible user device like notebook or PDA. This GSE provides all necessary operation for engine maintenance evaluation and producers' maintenance data server communication.

The main functions of the ground maintenance equipment are as follows:

- Data analysis and visualization, provision to service personnel of recommended actions to be taken when serving the power plant and carrying out scheduled activities,
- Trend monitoring and evaluation,
- Provision of short and long-term operation service recommendations based on engine condition trend evaluation and prediction,
- EMM configuration,
- Automatic report creation,
- Generating database over the entire engine lifecycle. Preparation and output of fault detection and elimination information, and service recommendations.

3. CP-CS mathematical model and simulations

Formulation of a model of controlled system is an essential part during the stage of design of its control system. Model is used for examination and prediction of the behaviour of the real system it represents, which could be in real-world very expensive, dangerous and even hardly feasible.

Model of the system is usually created on the basis of mathematical description. In engineering disciplines the mathematical model is usually described by a set of algebraic, differential or difference equations, the transfer functions or the state matrixes. These relations are mostly derived either by a mathematic-physical analysis of the system's phenomenons or by an experimental examination of the real system. Within the modeling of very complicated systems both approaches are combined. Aim is to design as precise model as possible, but also as simple as possible. These two requests go unfortunately against each other – usually the more precise the model, the more complicated it is.

A turboprop engine is a very complex and highly nonlinear system. The physical phenomenons involved cover domains such as solid and fluid mechanics, thermodynamics and electromagnetism.

All the model parts are based on the mathematical description of every single part, provided by their respective designers. The model consists of a VTPE (Virtual Turbo-Prop Engine), which forms the "system under control" and the CP-CS, which consists of the ECU/FADEC together with the fuel (FCEID) and propeller (PCEID) governors. The CP-CS is commanded by a control interface from the pilot's cabin. Structure of the VTPE model is based on dividing the whole engine into two basic parts, which can be solved separately. These main parts are a gas-generator (inlet, compressor, combustor and turbine) and a power turbine with gearbox and propeller. There is only thermodynamic power linkage between these two parts and the only hand over variable is the power transmitted from the gas-generator to the free turbine. Due to this fact the complexity of model is considerably reduced.

The CP-CS is developed in accordance with practices described in the V–cycle development methodology. Every block of the CP-CS has its own mathematical model in the MATLAB/Simulink computing environment. The interaction between the simulation blocks are shown in Fig. 4.

The VTPE model is precise enough for examination of its behaviour during flight at different aircraft speeds, heights, power extractions and outside conditions. Start of the engine, reverse mode, taxi and feathering are not possible to simulate.

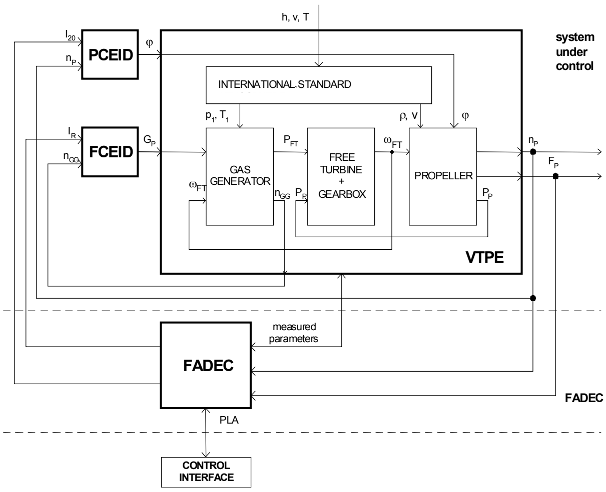

Fig. 4. Block diagram of the VTPE and CP-CS architecture

4. Development of fuel metering pump control system

Based on previous experience every development of a control system starts with definition of requirements and system modelling. A mathematical model describing all parts of the control system together with a system under control gives the developers an exact idea about system behaviour, reactions and ability to verify different control strategy and algorithms in the early stage of the development. In addition, the control system can be tested by means of hardware in the loop simulation, e.g. using tool such a dSPACE, completely without any previous hardware design. This is a considerable advantage since the team could precede many mistakes, dead ends and even damage of the first evaluation samples. Unquestionably, these are the benefits that considerably decrease the development time and costs.

The mathematical model of the control system with controlled BLDC motor consists of three basic parts: electrical, mechanical and sensing. The model was designed to implement as many as possible of the known motor parameters given by its producer and also as many parameters which describe the control system in the appropriate detail to closely match the real conditions. It is beyond the scope of this article to describe the whole mathematical model in detail; inquisite reader can find it in [9] or [10].

The important tracked values are amplitude of induced voltages in particular windings, winding currents, rotor position and acceleration of the rotor. An example of traced values is depicted in Fig. 5.

The starting phase of the rotor was chosen as the most important since this phase is the most critical during operation of the FMP. Therefore many algorithms were tested to achieve fast reaction and smooth acceleration at reasonable current flow level. Values provided by the simulations of the control system were used in the hardware design which was the next step of the project.

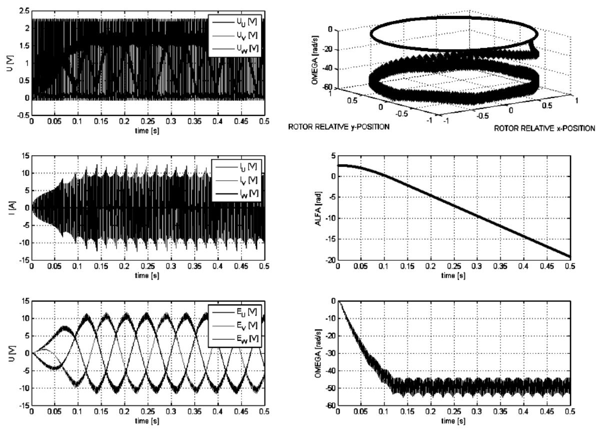

Fig. 5. Block diagram of the VTPE and CP-CS architecture.

5. HW design of the control system

The control system is designed as modular and it consists of three parts that can be interchangeable according to customer needs. The three basic modules are Control and Communication Unit (CCU), Power Electronics Unit (PEU) and I/O Unit (IOU). The control system architecture is shown in Fig. 6.

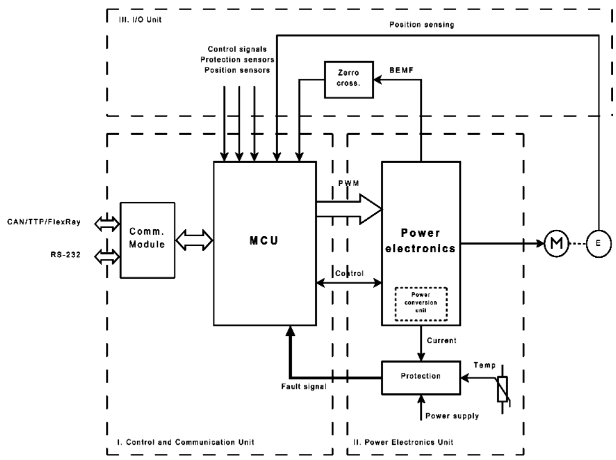

Fig. 6. Architecture of the electronic control system for EHA/EMA actuators

5.1 Control and Communication Unit

The main microcontroller is placed on the Control and Communication Unit (CCU). The CCU is replaceable according to application performance requirements and architecture of the control system. The core of CCU is created by a multipurpose microcontroller (MCU).

The CCU has an unified interface for all the analog and discrete signals that are used for control and communication with other control system modules. Using a unified interface enables replacement of the CCU in case of system enhancement or maintenance.

The electronic control system for the FMP can provide selected information of its internal states and measured values to the higher level control system via an internal communication network. The higher level control system can be a Flight Control Computer (FCC) or a multifunction avionic display placed in the pilot's cockpit.

5.2 Power Electronics Unit

The Power Electronics Unit (PEU) consists of full H-bridge that is created by six power switching transistors. Motion of the BLDC motor is controlled by switching power supply to the particular coils of the BLDC motor.

An integral part of the PEU is the Protection module that measures temperature, current and voltage on the BLDC motor. In case of any parameter exceeds a limit value the protection module generates a fault signal that enters into the MCU. Detection of the fault signal causes disconnecting of load from the power supply source.

5.3 I/O Unit

5.3.1 BLDC motor signals/sensors

Depending on actual configuration, the electronic control system could operate either in sensor or sensor-less mode.

In sensor mode signals from Hall sensors are used as feedback. These sensors are usually mounted inside the BLDC motor by its producer. These signals are triggered and used as inputs into the control MCU.

Sensor-less control mode operates on principle of sensing induced voltage caused by Back Electro Motive Force (BEMF) on one of three BLDC motor phases. Feedback is extracted by the means of BEMF and zero-cross detection.

Functionality and safe operation of the actuator is ensured by monitoring of selected parameters and restricting the actuator's fault operation. If one or more of the signals exceed its limit value, the fault is detected and appropriate action is taken.

5.4 Evaluation sample

The control system was designed to fit the requirement of mounting into the FMP to create a monolitic box with an explosion-proof design. The development run in accordance with the aviation standards RTCA/DO-254 (DO-254) and RTCA/DO-160F (DO-160).

The first evaluation sample is shown in Fig. 7.

Electronics of the control system is designed in a custom tailored shape with logical partitioning according to performed functions. Logical partitioning to control, power electronics and sensing board brings also the advantage of custom configuration and much simple service.

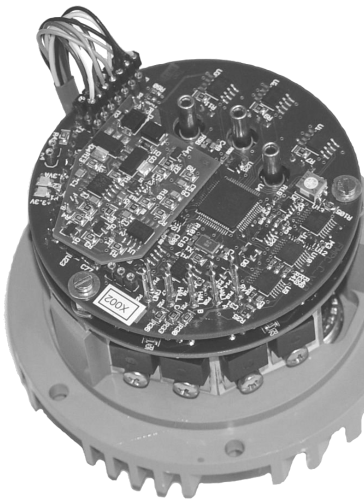

Fig. 7. The first evaluation sample of the control system for FMP

6. Control system software design

The main aim, that was taken into consideration, is that control system had to be portable and easy to implement on a common 16-bit MCU. Final control system is written in the C programming language and is implemented into a Microchip dsPIC MCU.

Algorithms are designed with respect to high criticality of the application, therefore no artificial methods or fuzzy control algorithms could be used. Requirements on high reliability also limit the code complexity, thus simple but efficient software algorithms are used where ever it is possible.

Software design was preceded by detailed decomposition of system requirements, interface definitions, data flow and control flow. These requirements and definitions expressively determined final form of source code.

Therefore their thorough evaluation was extremely important for design of control algorithms. Proper definition and evaluation simplified software development cycle and eliminated errors caused by further implementation of additional functions.

The control algorithm is designed according to the flowchart that is shown in Fig. 8. The algorithm consists of initialization part, motor start-up, closed loop control and interrupt service routines.

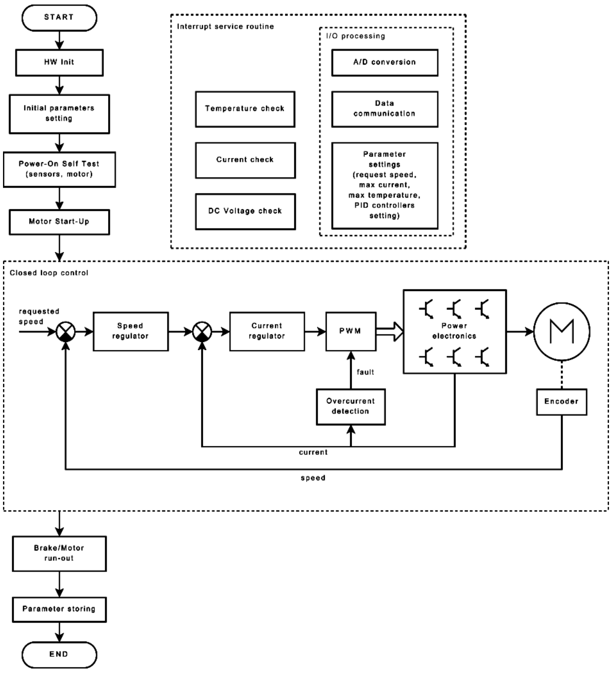

Fig. 8. Concept of the control system software design

6.1 Initialization

Initialization part serves for initial hardware set-up, parameter setting and power-on self test. During this stage all the parameters and values are checked against the standard values. In case of abnormal value or malfunction the control system issues warning and tries to re-initialize hardware again.

6.2 Motor start-up

In critical applications, it is necessary to ensure correct start-up of the motor. Thus, many simulations had been done before implementing the control algorithm into the controller. The motor start-up algorithm ensures reliable start-up of different types of BLDC motors.

6.3 Closed loop control

After initialization and motor start-up sequence, the control algorithm switches into the closed loop control. Closed loop control algorithms consist of the two nested PID controllers - the speed controller and the current controller.

The current regulator sets the desired value by means of PWM. It compares a desired value from superior speed regulator and measured current through the BLDC and sets output value upon their variance.

The speed regulator sets the desired value for the current controller. Actual rpm speed could by measured by Hall sensors or using a Back Electro-Motive Force (BEMF).

6.4 Interrupt service routines

Interrupt service routines serve for performing repeating tasks that evaluate critical values, such as power electronics temperature, current flowing into the BLDC motor, DC bus voltage, etc.

Separate interrupt service routines also serve for Input / Output processing and measurement. These especially involves:

- A/D conversion;
- data communication (via CAN or RS-232 data interface);
- parameter settings (parameter setting is based on data communication commands).

7. First evaluation sample test results

To evaluate performance of the control system and designed electronics two types of evaluation test benches were used. Firstly, the in-house developed evaluation test bench. First measurements and simulated dynamic testing were performed on this evaluator; different control algorithms were tested and controller variables were set.

Then the control system electronics was mounted on the FMP and performance tests were performed on an evaluation mock-up platform that simulates a real fuel circuit. These test were performed with help of an external company and the main interest were put on start and stop sequences of the FMP.

Start sequence of the FMP is shown in Fig. 9.

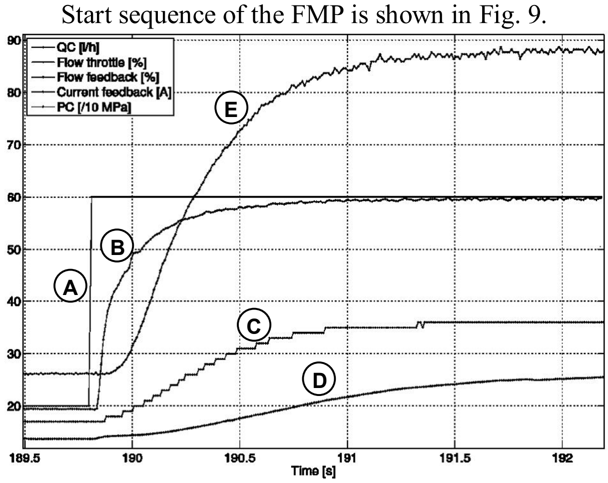

Fig. 9. FMP starting sequence measured on the fuel circuit simulator

In Fig. 9 the green line (**A**) represents the requested value of the fuel flow. The measurement monitors reaction of the system on setting the requested value of the fuel flow to 60%.

The red line (**B**) represents the fuel flow which is measured and computed by the control electronics. It is evident, that measured fuel flow gradually increases up to the requested value without overshoot.

The brown line (**E**) indicates the real fuel flow in the system measured by an external sensor. Real value of the fuel flow traces the fuel flow measured by electronics with a slight time delay and slower increase which is due to physical characteristics of the mock-up system (gradual increase of fuel pressure, time delays caused by fuel flow throught system).

The pink line (**C**) represents pressure in the system and the blue line (**D**) indicates peak current values during PWM cycle as were measured by electronics on the H-bridge.

Start sequence of the FMP is shown in Fig. 10.

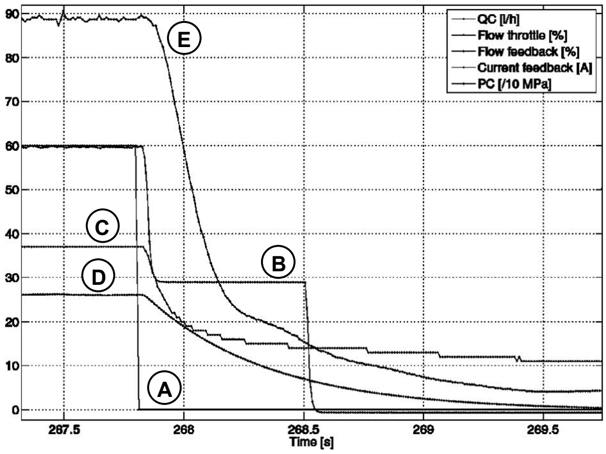

Fig. 10. FMP stopping sequence measured on the fuel circuit simulator

In Fig. 10 the color representation of individual measured values stays the same as in Fig. 9. After setting the desired value of the fuel flow to zero, the control system of the FMP stops the BLDC motor and the fuel flow gradually decreases to zero. Stairy shape of the fuel flow (red line (**B**)) measured by electronics is caused by overflow of the timer which is used for measurement of motor rpm. Fuel flow measured by the external sensor indicates gradual decrease althought the BLDC motor is not running. This short term decrease of the fuel flow is due to inertial flow inside the mock-up system.

8. Conclusions

The development and certification of any new equipment for aerospace industry requires – except the best quality, performance, safety and reliability – also compliance to strong regulation standards. The use of COTS components and tools seems to be one of possible choices to reduce the development time and costs. We have proven, that these tools are already available on the market and ready to use also for the development of such a critical control application like the Complex Power-plant Control System for a small civil aircraft.

Mathematical models were created following the detailed mathematical description provided by the aircraft, engine and other subsystems designers. The model of the VTPE was designed and the control algorithms for FADEC were implemented. Control functions were simulated for several different configurations and the results showed applicability of the newly designed CP-CS for aircraft engine control. In addition, detailed modelling allows the designers to precisely analyse individual subsystems of the engine and control system and thus prevent possible future redesigns.

Next step in the development cycle is to convert the model of the VTPE into a HW simulation which shall provide will be the model of VTPE converted to HW simulation which will provide real-time model of the engine.

The FADEC's algorithms will be converted to the target HW and the hardware in loop test will be done. We expect that this methodology will gain time and cost reduction of development life-cycle, that is in fact one of the objectives of the project CESAR.

9. Acknowledgment

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КОМПЛЕКСНІ СИСТЕМИ УПРАВЛІННЯ Й КОНТРОЛЮ СИЛОВОЇ УСТАНОВКИ ДЛЯ НЕВЕЛИКИХ СЕРВІСНИХ ЛІТАКІВ І СУЧАСНІ ТЕНДЕНЦІЇ В ОБЛАСТІ ВИКОНАВЧИХ МЕХАНІЗМІВ

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Дана стаття описує мотивацію для використання готових комерційних виробів для розробки систем критичного управління в авіакосмічній промисловості. Представлено базову модель V-циклу, її переваги й зображені методи розробки, які отримані з моделей MATLAB/Simulink для реального цільового застосування. Увага також звернена до сертифікаційних вимог FAA/EASA ([6, 7, 8]) і конкретно процесу сертифікації нового авіаційного обладнання. Ці методи використовуються під час розробки Комплексної Системи управління Силової установки для малого цивільного літака, також описані їхні функції й автономні вузли. Описано розробку Комплексної Системи управління Силової установки заснована на моделі, також наведені результати моделювання.

Ключові слова: "інтелектуальні" виконавчі механізми, виконавчий механізм EHA/EMA, розподілені системи управління, BLDC моторне моделювання.

КОМПЛЕКСНЫЕ СИСТЕМЫ УПРАВЛЕНИЯ И КОНТРОЛЯ СИЛОВОЙ УСТАНОВКИ ДЛЯ НЕБОЛЬШИХ СЕРВИСНЫХ САМОЛЕТОВ И СОВРЕМЕННЫЕ ТЕНДЕНЦИИ В ОБЛАСТИ ИСПОЛНИТЕЛЬНЫХ МЕХАНИЗМОВ

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Данная статья описывает мотивацию для использования готовых коммерческих изделий для разработки систем критического управления в авиакосмической промышленности. Представлена базовая модель V-цикла, ее преимущества и изображены методы разработки, которые получены из моделей MATLAB/Simulink для реального целевого применения. Внимание также обращено к сертификационным требованиям FAA/EASA ([6, 7, 8]) и конкретно процессу сертификации нового авиационного оборудования. Эти методы используются во время разработки Комплексной Системы управления Силовой установки для малого гражданского самолета, также описаны их функции и автономные узлы. Описана разработка Комплексной Системы управления Силовой установки основанная на модели, также приведены результаты моделирования.

Ключевые слова: "интеллектуальные" исполнительные механизмы, исполнительный механизм EHA/EMA, распределенные системы управления, BLDC моторное моделирование.

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