

Application of Model Based Functional Specification Methods to Environmental Control Systems Engineering

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ABSTRACT

The paper presents an innovative approach for the functional specification of complex and highly integrated aircraft control systems, such as the Environmental Control System (ECS), by applying model based specification methods. Complexity and effectiveness of modern ECS have significantly increased during the last few years along with development of new technologies and innovations in control engineering as well as digital data distribution and processing. Efficient management of cabin air flows on the one hand makes the ECS more energy-saving and on the other hand more complex with regard to its functionality and interaction with other interfaced aircraft systems. Numerous data interfaces to other systems and a high degree of automation are typical for a modern ECS.

The aircraft manufacturer specifies the entire ECS functions and its interactions within the aircraft. Following the conventional approach, a textual functional specification is written containing requirements for automatic control and monitoring for all ECS functions and interactions with other systems. Based on that, subcontracted suppliers develop the ECS hard- and software. Due to the large number and complexity of functions the textual functional specification is difficult to fully validate and may suffer from misinterpretation by the system supplier, inconsistencies and undetected errors before first prototypes are ready to run on a system test bench.

This very often leads to iterative, expensive and time consuming soft- and hardware development cycles. It is shown in the paper how ECS functions can be more effectively specified using model based functional

specification techniques, which have been derived from software engineering. With these techniques, the textual specification is replaced by an executable specification model. This enables the aircraft manufacturer to consistently specify the ECS in a uniformly structured manner with fit-for-purpose tools and the ability to simulate and to validate its specified functions and interfaces before prototypes are tested on a system test bench. Finally, the paper gives the benefits of this approach for an ECS development from a project management perspective. These are shorter development times and reduced number of errors in system control resulting in reduced development costs.

1. INTRODUCTION

Development of today's civil aircraft systems follows well structured and established processes, which have been set up by the aircraft manufacturers based on process related requirements and needs given by the airworthiness authorities (EASA [1], FAA [2]) as well as company internal standards and internationally recognized standards, such as those given for instance by ISO [3], INCOSE [4], IEEE [5], RTCA [6], SAE [7]. Careful application of these processes shall guarantee fast and efficient development and integration of modern complex systems into the aircraft with regards to its mechanical, electrical, electronic, and data communication interfaces.

The aircraft manufacturer leads the aircraft systems development by applying these processes. They specify the system's needs and functionality according to specific requirements given by the airworthiness authorities, airlines/ customers as well as from the aircraft manufacturer itself. At a certain stage of the development process, the aircraft manufacturer subcontracts the system development to

certified aircraft system suppliers which further develop subsystems, software, hardware, and equipment as part of the entire aircraft system which is to be developed in accordance to the system specification set up by the aircraft manufacturer. Both, the aircraft manufacturer as well as the suppliers and sub-suppliers being involved in the system development strictly need to follow the above mentioned processes in order to realize a properly integrated and operating system according to the aircraft specifications. On top of well defined processes to be applied at any stage and phase during system development an important key element of a successful development is a strong project management throughout all responsible participants. It drives and supervises the fulfillment of the process rules in order to complete the system within the given time frame and budget in line with the specifications.

The aircraft manufacturer continuously tries to improve the processes to be applied in order to overcome weak points that are contained and which he has experienced during systems engineering in former aircraft programs. Furthermore, integration of new technologies into the aircraft and growing system complexity drives the need for adaptation of development processes. This becomes even more important when aircraft manufacturers change their subcontracting policy and extend the packages of subcontracted development activities to external suppliers. Clear responsibilities in engineering work share are an important aspect for obtaining good results in terms of cost, time, performance, and quality of the product.

The current paper presents a novel approach for the aircraft system development process. This approach has been derived driven by certain disadvantages which have been experienced in previous development processes and which have often led to iterative development cycles. The disadvantages mainly result from the fact that functional system specifications are written as a document that contains verbally expressed functional requirements rather than un-ambiguous requirements that are written in a formal or semi-formal language. The paper analyses these disadvantages and shows how the application of model based functional specification methods to system development of civil aircraft helps to overcome the disadvantages and consequently improve aircraft system development processes. The methodology originates from software engineering and has been adapted to systems engineering processes over the past few years. It is demonstrated how the use of it makes the specification of aircraft system functions more effective in comparison to conventional specification technologies which are mainly paper based and which consist of textual requirements for the description of system functions to be developed. Correct, clear and unambiguous specification of the system functions are very important for its development, even more when major parts of the system development are subcontracted to external suppliers. These subcontractors need to fully

understand and retrace the complex functions of the system and its operational modes and interactions inside the system and with other aircraft systems in order to be able to continue a proper development based on the specifications. The trend over the last few years has lead system suppliers to an increased responsibility and perimeter in their system development activities. Especially under these circumstances a clear functional system specification as the interface between aircraft manufacturer and system supplier is very important in order to prevent the supplier from developing erroneous systems or components. The paper presents the application of model based functional specification techniques to Environmental Control Systems (ECS) as an example for a complex aircraft system and how this will lead to minimize errors in specifications and definite interpretations of the specifications by the supplier resulting in a more effective system development with regards to time, cost, quality and performance.

The main global objective of an Environmental Control System (ECS) is to ensure passenger and crew comfort under extreme external climatic conditions the aircraft is exposed to during its missions and various normal and abnormal operational cases. An ECS is a mechanical-pneumatic system using high-pressure bleed air from APU and engines in order to pressurize the aircraft fuselage and to provide fresh conditioned air to the different compartments of the aircraft. It is built with a high degree of automation in order to relieve flight and cabin crew from manual interactions with the system during the various operational modes in flight and on ground. It shall guarantee passenger's safety, comfort, and healthiness through its safe, reliable operation together with its contribution to aircraft efficiency. Main tasks of the ECS are generation of fresh air, ventilation of cabin, cargo and dedicated compartments and devices such as avionics, extraction of used air to overboard, control of compartment temperatures, control of cabin air pressure, and finally control of compartment humidification. These characteristics make the ECS a highly complex and distributed system in a civil aircraft.

The paper first gives an introduction into ECS and the Ventilation Control System (VCS) as one of its main subsystems. Next section describes weak points and problems occurring when conventional system development processes are applied using textual and paper based specifications. The Model Based Systems engineering (MBSE) approach is introduced in a following section as a novel systematic method for systems engineering. Afterwards it is described, how a systems detailed functional specification can be established applying MBSE techniques. The resulting functional specification model replaces the conventional paper based functional specification. This is demonstrated using the VCS as an example system to set up a functional subsystem specification model. At the end of this paper main

conclusions are drawn, and finally an outlook to further research activities is given.

2. ENVIRONMENTAL CONTROL SYSTEM: ARCHITECTURE AND FUNCTIONS

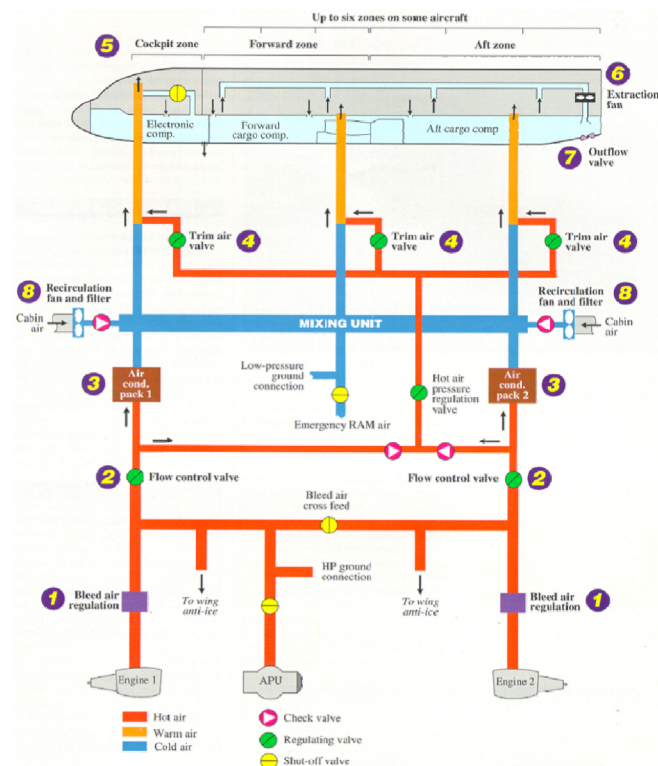


Figure 1. Schematic of an Environmental Control System (simplified)

Outside air compressed by the aircraft engine is taken at two ports bleeding air from two different compressor stages. Depending on the available pressure and the pressure required for pressurization and air conditioning one of those ports is utilized whereas the other one is closed. The pressure of this bleed air is regulated to a given pressure set point by a pressure control valve. Due to the high pressure ratio achieved in the engine compressor the bleed air leaves this pressure control valve at high temperatures between 300 and 400 °C. A steel heat exchanger is used to reduce the temperature in a first step down to 200°C for normal operation cases. This component called pre-cooler utilizes air from the engine fan as primary heat sink. A fan air valve controls the amount of engine fan air to regulate the bleed air temperature (1). From the pre-cooler the bleed air is distributed to the different consumers as wing anti-ice system, fuel inerting system, engine starter valves and the air conditioning pack (3) as the core component of the ECS. A flow control (2) valve regulates the mass flow of bleed air into the air condition pack to maintain certified levels of

outside air and correct cabin pressure levels. A common technology of air conditioning pack is based on the three wheel bootstrap cycle. This cycle is a reverse Joule cycle using ram air as primary heat sink and a turbine for expansion cooling. An internal compressor driven by the turbine is used to increase efficiency by introducing an intermediate cooling step. The bleed air expanded in the turbine is mixed with air bypassing the turbine to control the temperature to the required level. Air from the aircraft cabin is recirculated by ventilation fans and filtered in high efficiency particle filters (8) before it is mixed with outside air from the air conditioning pack in the mixing unit. Air recirculation as one of the core functionalities of the ventilation system helps to increase humidity levels for passengers and increases supply temperatures for the aircraft cabin to ensure cabin comfort. As modern aircraft include several temperature zones in the passenger cabin (5) the temperature of the air provided by the air conditioning pack needs to be individually controlled for each of those zones. This task is performed by the temperature control system (4) which uses hot air taken downstream of the flow control valve to fine tune the supply temperature for each passenger zone. As part of the ventilation system which ensures proper air flows into all aircraft compartments and provides cooling for various types of equipment an extraction system is installed (6) which extracts galley and toilets to prevent odors entering the passenger cabin. Finally, part of the cabin air leaves the aircraft through the outflow valve. The outflow valve (7) controls the cabin pressure to safe and comfortable levels by regulating the mass flow of air leaving the aircraft.

3. INNOVATIONS IN VENTILATION CONTROL SYSTEMS ENGINEERING

The Ventilation System (ATA21-20) as a part of the ECS (ATA21-00) for civil aircraft in general distributes the air within the aircraft's fuselage as well as in dedicated unpressurized areas. It has several different tasks according to the split into its several ATA sub-chapters [8], which are

- Air Distribution / Recirculation,
- Cockpit Ventilation,
- Cabin Air Extraction,
- Unpressurized Compartment Ventilation,
- Avionics Equipment Ventilation,
- Crew Rest Compartment Ventilation,
- Cargo Compartment Ventilation, and
- Commercial Equipment Ventilation.

It contains various types of equipment, such as electrically and pneumatically driven fans, valves, actuators, pressure sensors, flow sensors, temperature sensors, and electronic controllers as well as a large and wide ductwork system

which is spread over the whole aircraft. All devices and pieces of equipment of a Ventilation System are clearly assigned to one or more of its subsystems as listed above according to their individual functions. Figure 2 shows an example Ventilation System architecture including the amount of airflow entering the aircraft, the cabin and further individual airflows in relation to each other. The calculation is standardized to cabin air inflow which is equal to 100%. The picture also shows system inherent applications for electrical fans driving the air volume flows through the system and providing sufficient air exchange rates. Certain cabin air exchange rates are especially required by the airworthiness authorities.

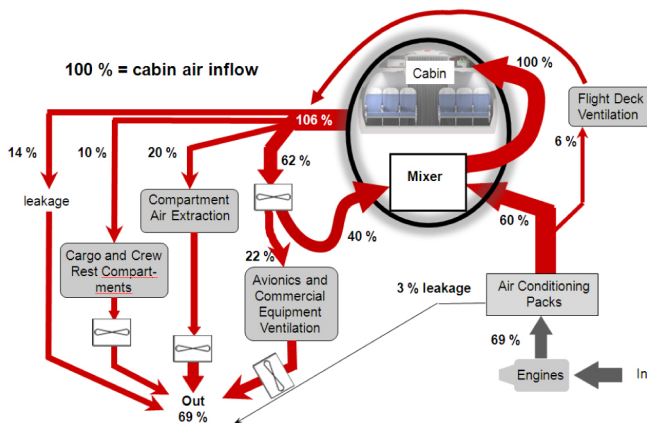


Figure 2. Simplified overview of aircraft air distribution, realized by the Ventilation System

It is characteristic for the Ventilation System that it has a high degree of functional interaction with other interfaced systems of the aircraft, such as all other systems in the scope of ECS, but also cockpit indication and control systems, smoke detection system, doors system, in-flight entertainment system, electric systems, to mention only a few examples. An important thing that is additionally required from the Ventilation System is, that its operation shall be fully automatic under all normal operating conditions and abnormal operating conditions as far as possible. This is required to minimize workload for the flight and cabin crew. Together with the aforementioned characteristic of the Ventilation System's complex embedding into the aircraft with interfaces to numerous further aircraft systems, this drives the need for intelligent electronic controllers to facilitate data exchange with other systems and to automate the system's control. In the past, aircraft system control has often been realized by the installation of hardwired logic using for example relays or relay boxes together with individual data communication between two systems. Today's complex aircraft systems include process computers running control software and wide modern communication networks, like Ethernet derivatives for aviation or CAN buses, so that a physical communication between two co-operating aircraft

systems can easily be established by access to a commonly used network. An automated Ventilation System, using either past or modern control technologies, is called "Ventilation Control System" (VCS).

Figure 3 shows a schematic of a today's VCS. Modular process computers (Core Processing Input/Output Modules - CPIOM) host the VCS control software controlling and monitoring the system's states by reading and commanding the various components, such as fans, valves, sensors etc. CPIOMs are connected to an aircraft wide Avionics Full Duplex Switched Ethernet (AFDX) [9] network and allow fast and digital communication among each other and with other systems. System internal buses, such as CAN buses, can additionally be used to control and monitor more complex VCS components having individual controllers or Remote Data Concentrators (RDC). These are special input/output controllers with dedicated hardware interfaces to the VCS components connected to them. The RDCs translate electrical analogue and discrete signals from the components into digital bus signals to be sent to the CPIOMs and vice versa. Today's trends go towards a standardization of CPIOM's and RDC's hardware and operating systems, so that they can be applied to many different aircraft control systems and can be configured for individual use by software configuration resp. loading of system specific control software applications, like a VCS software.

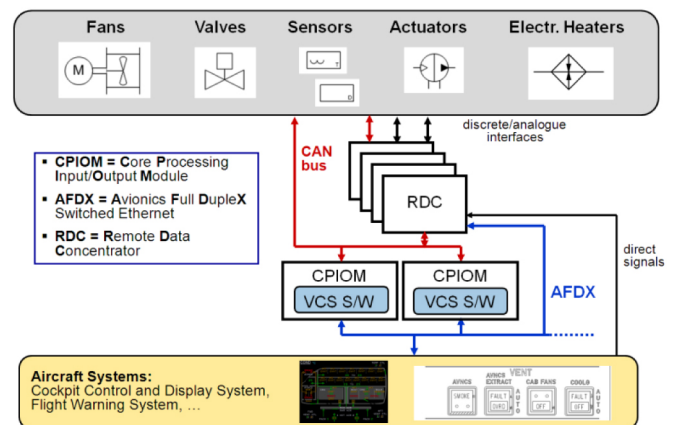


Figure 3. Schematic of Ventilation Control System with regards to components and controls

Control functions for a VCS are generally integrated into a control software application which itself is very complex because it hosts all control and monitoring functions for each VCS subsystem resp. component. Single VCS functions can often be expressed using Boolean logic with several inputs. Hence, complexity of ventilation control is given due to the large number of relatively simple control functions to be executed in parallel rather than due to single complex control laws. Furthermore, most parts of VCS subsystems can be characterized in an idealized manner as "Discrete Event

Systems”, which are defined as follows: “A *Discrete Event System* (DES) is a discrete-state, event-driven system, that is, its state evolution depends entirely on the occurrence of asynchronous discrete events over time.” Key properties of DES are that the state space is a discrete set and that the state transition mechanism is event-driven [10]. This applies to a large extent to civil aircraft VCS.

In the following, the mixer unit and recirculation system as an important VCS subsystem will be explained in more detail, because this shall be used in the final sections of this paper as an example subsystem to which the new specification method is applied.

The mixer unit mixes outside air coming from the packs with recirculated air which is extracted from the cabin. When the aircraft is in cruise, recirculated air is relatively warm and humid whereas outside air is cold and dry. Both types of air are blown into the mixer at its bottom. Applying fluid mechanical laws to the design of the mixer unit's geometry ensures a good mixing inside the unit. This provides that all individual branches at the mixer head distributing the air to the different cabin zones get equal air temperatures. Ideally, the mixer unit can be modeled as shown in [figure 4](#). The steady-state model contains two points, one at the bottom and one at the top of the mixer, where differential air pressures are calculated. A constant total mixer air flow $\dot{m}_m$ results from constant pressures at mixer bottom and mixer head.

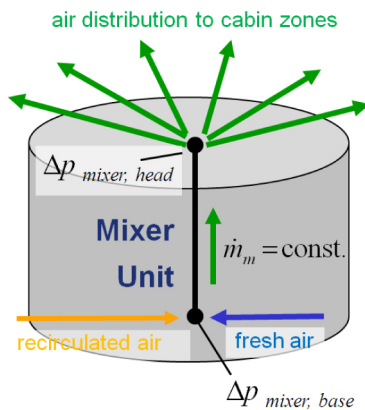


Figure 4. Mixer Unit: Steady-state model

The total mixer air flow depends on the pressure difference between mixer head and mixer bottom according to pressure drop [equation \(1\)](#).

$$\sigma_m (\Delta p_{\text{mixer, base}} - \Delta p_{\text{mixer, head}}) = k_m \cdot \dot{m}_m^2 \quad (1)$$

with

$\Delta p_{\text{mixer, base/head}}$:= air pressure difference between mixer base resp. head and cabin pressure
 $\dot{m}_m$:= air mass flow from mixer bottom to mixer head
 $\sigma_m = f(T, p)$:= air density correction
 $k_m = \text{const.}$:= pressure drop value between mixer bottom and head

Air management functionality allows a variation of the ratio between recirculated air and fresh air to the current demand. This ratio can thus be regulated according to actual conditions of cabin, aircraft and ECS, depending for example on number of seats, number of boarded passengers, and aircraft altitude. The aim of this regulation is to reduce bleed air consumption of the air conditioning system and consequently fuel consumption of the aircraft.

To realize that, the air generation system varies its produced outside air flow into the mixer unit according to the actual needs. Speed controllable recirculation fans react on the varying outside air flow and compensate an increase or decrease of outside air by decreasing resp. increasing their speed and the resulting recirculated air flow. [Figure 5](#) shows the basic control principle of the recirculation system. High pressure recirculation fans are equipped with modern software controlled frequency inverters together with a superimposed speed control loop as part of the electrical drive cascade control. In order to keep the total mixer air flow at a constant rate this blue marked cascade control is completed with a further outer control loop regulating the differential mixer head pressure to a constant reference value Δp_{ref} . This quantity is the difference between mixer head and cabin air pressure. Controlling Δp_{ref} to a constant value results in constant air flow through the branches connected to the mixer head and providing air into the cabin zones and further compartments. The mixer pressure control cascade must be designed fast enough to be able to compensate the variations of outside air flow into the mixer which occur as disturbances to the mixer pressure control.

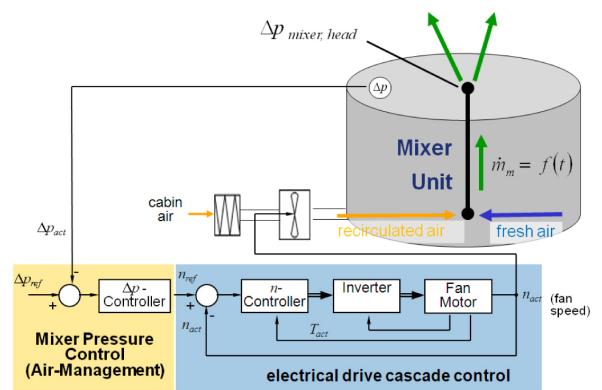


Figure 5. Mixer Unit: Dynamic model with mixer pressure control