

Virtual Integration and Testing of Multifunctional Fuel Cell Systems in Commercial Aircraft

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ABSTRACT

This paper focuses on the virtual integration and test approach used for the evaluation of an automation system developed for the multifunctional operation of fuel cells in commercial aircraft. In order to accomplish the virtual integration a model of the overall automation system is linked with a dynamic model of the complete fuel cell system. For this purpose a modeling approach for complex physical systems is described in this paper. During virtual testing various simulation runs are executed based on automatically generated test cases, which cover a complete flight mission. For this reason a flight mission is modeled as a Statechart that includes next to time- based flight phases also potential events and malfunctions (e.g. engine flame-out, cargo fire). An algorithm is described, which can find all possible state combinations including parallel event sequences. Afterwards test cases are automatically generated using segmented flight profiles in order to integrate atmospheric pressure and temperature as well as airspeed. During each simulation run so-called evaluation agents analyze and compare certain operational states with corresponding specifications. The global results are visualized using three-dimensional plots. The presented approach is illustrated in this paper using a simple example of a fuel cell system that operates multiple functions during a flight mission.

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INTRODUCTION

The integration of the fuel cell technology in commercial aircraft is driven by ecological objectives as well as performance benefits in the scope of a More-Electric-Aircraft. Due to ACARE Flightpath 2050 the aviation industry is increasingly focussing on reduction of polluting emissions during flight and ground operations [1]. In this context the fuel cell technology is promising, because the exhaust contains no pollutants and fuel cells can operate silently. Moreover, the high efficiency of fuel cells is beneficial considering an increasing demand of electrical energy in future aircraft. But, the power density of fuel cells is lower compared to conventional gas turbines. In order to deal with resulting weight penalties current research activities focus on the utilization of fuel cells for multiple functions on board an aircraft [2,3]. Components of this multifunctional fuel cell system as well as integrated functions are shown in [Figure 1](#).

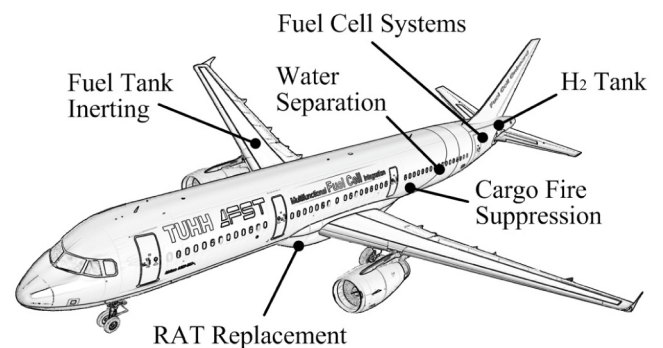


Figure 1. Overview of multifunctional fuel cell integration

The electrical power generated by the fuel cells enables an independent ground operation. During flight fuel cells can be used as an alternative and dissimilar source of electrical power, for example in case of emergency. Moreover, air-breathing fuel cells provide exhaust gas, which has low oxygen content with a high amount of water. This oxygen-

depleted air can be used for fuel tank inerting in order to achieve safety issues. Furthermore, the oxygen-poor air is capable to suppress a fire in the cargo bay. The water produced by the fuel cells shall be separated and used in the water system of the aircraft [2,3].

Virtual Integration and Test Approach

The development of new aircraft systems is challenging, especially when the integration focuses on a multifunctional approach. Figure 2 shows how model-based and virtual methods can enhance the common V-Model of the development process [4].

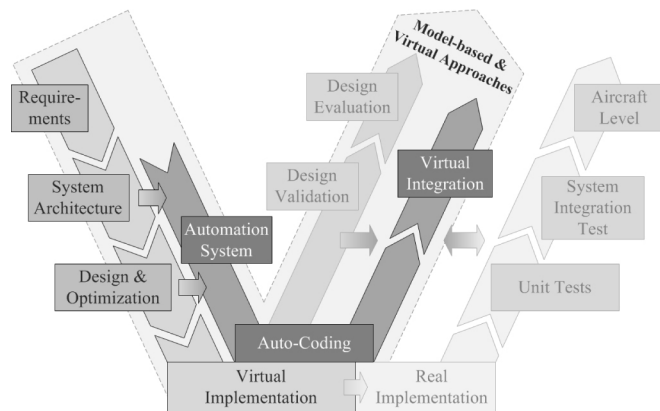


Figure 2. Enhanced model-based development process [4]

On the left branch model-based approaches can support the design and optimization process of proper system architectures. In this regard simulation studies enable the evaluation and validation of architectures with respect to total weight and overall system efficiency [5,6].

Beside the design of system architectures suitable control and monitoring concepts have to be developed and evaluated. The model-based design of control and monitoring functions can be done by using graphical specification methods, e.g. Signal Flow Charts and Statecharts [7]. In order to evaluate the interaction of all control and monitoring functions the virtual integration approach can be useful. Especially in early development phases virtual integration can enable the identification of inaccurate specifications, which are usually found during real integration tests. In this context, coupling effects between connected subsystems are of particular interest. Due to the avoidance of faults and a better system understanding virtual integration enables the reduction of development costs. This benefit has already been shown in other research projects, e.g. in the scope of high lift systems where virtual tests support real tests [8].

Inspired by the usage in [9] and [10] virtual integration stands in this paper for the connection of automation software with an overall dynamic system model in order to test all functionalities during possible flight missions. In this context virtual testing means the actual execution of various simulation runs and the evaluation of results.

The concept of the virtual integration and test approach used for the multifunctional fuel cell system including the overall automation software is shown in Figure 3 [4,11]. The models of all required control and monitoring functions are collected in an appropriate model library. Based on this library the complete automation system can be designed for the virtual integration. The physical models of all involved system components are located in a second model library. By combining the component models overall system architectures can be built and investigated during virtual testing.

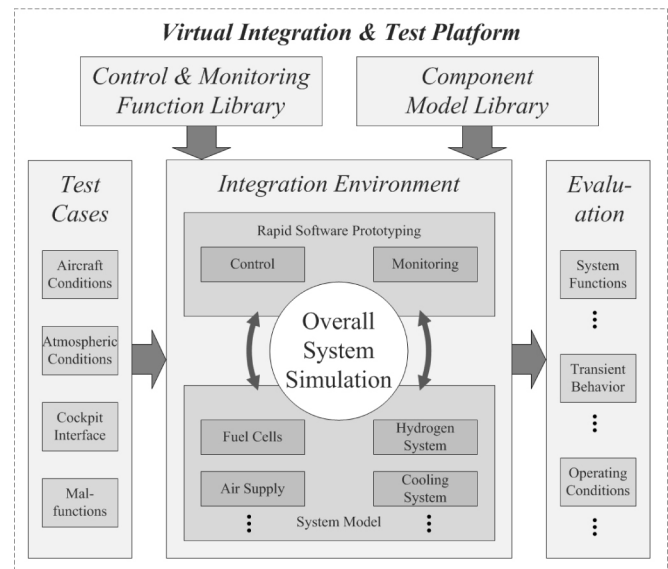


Figure 3. Overview of virtual integration and test approach

Virtual tests are conducted using test cases that stimulate the interface of the automation software as well as the boundary conditions of the system model. Test cases contain discrete events as well as time-based aspects. Discrete events are caused by cockpit systems or by fault events during a flight mission. Time-based behavior is given by changing atmospheric and aircraft conditions during different flight phases. The evaluation of each test case is done by using so-called evaluation agents. These agents can be implemented for a wide range of individual requirements. Finally, the results are processed and visualized.

The described concept of the virtual integration and test approach is implemented as software that is based on MATLAB from The MathWorks, Inc.

MULTIFUNCTIONAL OPERATION OF FUEL CELLS

The multifunctional integration of fuel cells in commercial aircraft is challenging, because several aircraft systems are involved. Moreover, the fuel cells shall fulfill different functions during a flight mission [2,3]. In Figure 4 several underlying functional requirements are illustrated [7].

In this paper the functions ground [12] and emergency power [13] as well as fuel tank [14] and cargo bay inerting [15] are used as examples for the multifunctional operation during a flight mission. During power operations the primary task of the fuel cells is to provide the demanded amount of electrical energy. In contrast to this, the primary task during inerting is to deliver the demanded amount of air with oxygen content below 10 % (vol.) [16] and a certain water amount. For fuel tank inerting dry inert gas is required [5]. Whereas for cargo inerting wet inertgas is suitable [15].

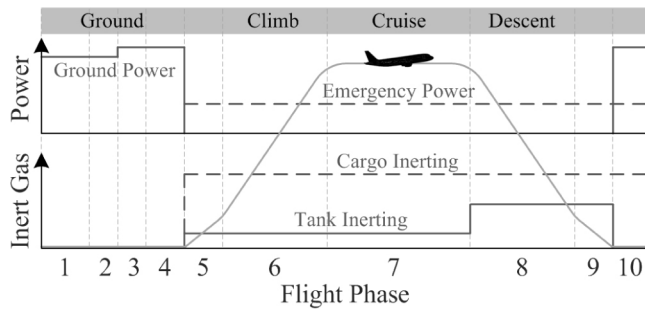


Figure 4. Power and inert gas demands during flight mission

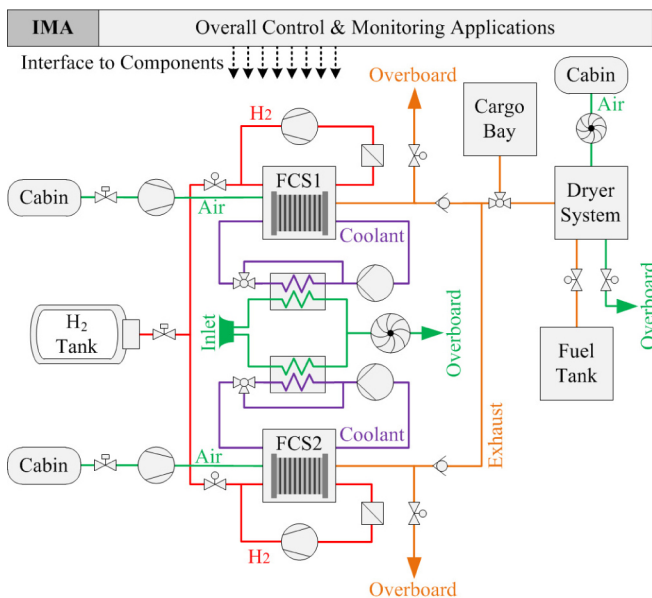


Figure 5. Overview of MFFC System architecture

Based on these requirements several system architectures are investigated during the development process [5]. Figure 5 shows a simple architecture that is used exemplarily in this paper. The architecture is based on two fuel cell stacks, which are supplied with compressed cabin air [17]. Both fuel cell stacks are capable to provide power to the electrical system as well as air to the cargo bay and fuel tank inerting system. During ground operation the demand of electrical power shall be provided by both fuel cell stacks. Whereas the inerting functions during flight operation can be provided by only one

fuel cell stack. This enables the utilization of the other fuel cell system for the generation of electrical power in case of emergency. As long as this is not required, the second system remains passivated.

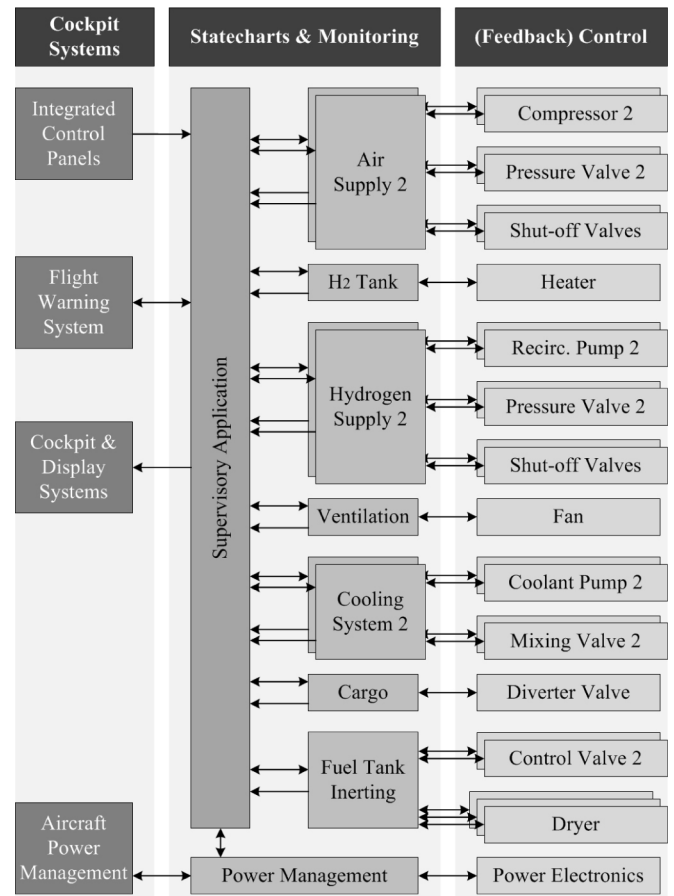


Figure 6. Overview of MFFCS automation system

In order to fulfill all functions automation software is required, which has to control and monitor the overall system. As indicated in Figure 5 all software functions and applications shall be executed on IMA that is a generic and distributed avionics platform. The operational state of the multifunctional fuel cell system can be influenced by controlling components, e.g. compressors, pumps, fans, valves. The monitoring is based on sensor values and the feedback of actuators. Figure 6 shows the automation system that is implemented in order to control and monitor the simple example of the presented multifunctional fuel cell system. The architecture of the automation system is structured according to a hierarchical approach [7]. On the lowest level the feed-forward or feedback control algorithms for the involved components are implemented. On the next hierarchical level dedicated Statecharts for each subsystem are specified. These modules include local functions:

- Startup procedure of subsystem,
- Determination of set points for feedback control.

- Shutdown and passivation procedure of subsystem,
- Monitoring of components, observation of system state, fault detection and evaluation,
- Safety configuration to prevent critical system states.

Moreover, a supervisory application is implemented in order to manage all system functions with respect to the overall operating mode [7]. This includes the evaluation of the current flight phase and further cockpit signals in order to decide which fuel cell stack and subsystem must be active or passive. Furthermore, the supervisory application interprets the fault messages of the subsystems and commands global reactions.

PHYSICAL MODELING APPROACH

The objective of virtual integration is the closed loop test of a system model connected with the overall automation software in the scope of possible flight missions. For this purpose an appropriate model of the physical system is required, which has to fulfill the following aspects [4]:

- Relevant physical domains and their interdependencies,
- Dynamic behavior for any operating points,
- Robust initialization and simulation,
- Realistic interfaces of actuators and sensors,
- Test case driven interfaces to the environment.

In order to design models in a clear and structured way the object-oriented and acausal modeling language Simscape from The MathWorks is used. This language enables the implementation of mathematical equations for the physical behavior in dedicated blocks. These blocks are connected by domains, in which the interface variables are defined. A domain contains on the one hand potential variables Ψ and on the other hand flow variables Φ . Additionally, a domain can be branched. The following equations describe the mathematical relationship at a junction [4]:

$$\Psi_1 = \Psi_2 = \Psi_3 = \dots \quad (1)$$

$$\sum_{i=1}^n \Phi_i = 0 \quad (2)$$

With regard to the simulation of complex system architectures considering the specified aspects an optimized modeling strategy is required. In the following the modeling approach is presented, which is used to design the multifunctional fuel cell system with all involved components and relevant physical interdependencies.

The used approach is based on the systematic breakdown of the overall system behavior in basic physical effects [18]. In general a physical flow Φ is caused by the difference between two or more potentials ($\Psi_1, \dots, \Psi_n$). This resistive effect can be described by the general relationship [4]

$$\Phi = f(\Psi_1, \dots, \Psi_n) \quad (3)$$

Dynamic system behavior can be integrated using capacitive and inductive effects. A capacitive effect is generally given by the equation [4]

$$\frac{d\Psi}{dt} = f(\Phi_1, \dots, \Phi_m) \quad (4)$$

Hence, the time derivative of a potential depends on associated physical flows. The inductive effect can be expressed by [4]

$$\frac{d\Phi}{dt} = f(\Psi_1, \dots, \Psi_p) \quad (5)$$

Accordingly, the time derivative of a physical flow depends on corresponding potentials. The required functions f can be found depending on the specific effect and domain.

Modeling Example

Beside the physical effects the systematic structuring and the definition of the domains are important [4]. These aspects are described in the following using the example of the air supply including the fuel cell cathode. Shut-off valves and further pipes are neglected in this simple example. Figure 7 shows the model structure of this part of the multifunctional fuel cell system.

The blocks represent the distribution of physical effects. In addition, the corresponding variables are specified. Since the fluid inertia is neglected only blocks with resistive and capacitive behavior are implemented. In a capacitive block all local potentials are initialized and computed. The resistive blocks contain the computation of flows depending on the neighboring potentials. The interfaces between the blocks are defined using so-called Balanced Domains. This type of domain is characterized by defining a corresponding flow variable for each potential variable. An overview of used Balanced Domains is given in Table 1 [4].

Table 1. Definition of used Balanced Domains

Domain	Potential	Flow
Air	p_{air}	$\dot{m}_{air}$
	$\xi_{O_2,air}$	$\dot{m}_{O_2,air}$
	$\xi_{H_2O,air}$	$\dot{m}_{H_2O,air}$
	T_{air}	$\dot{H}_{air}$
Cathode	$p_{O_2,ca}$	$\dot{m}_{O_2,ca}$
	$p_{N_2,ca}$	$\dot{m}_{N_2,ca}$
	$p_{H_2O,v,ca}$	$\dot{m}_{H_2O,ca}$
Heat	T_{heat}	$\dot{Q}_{heat}$
Rotational	ω	τ

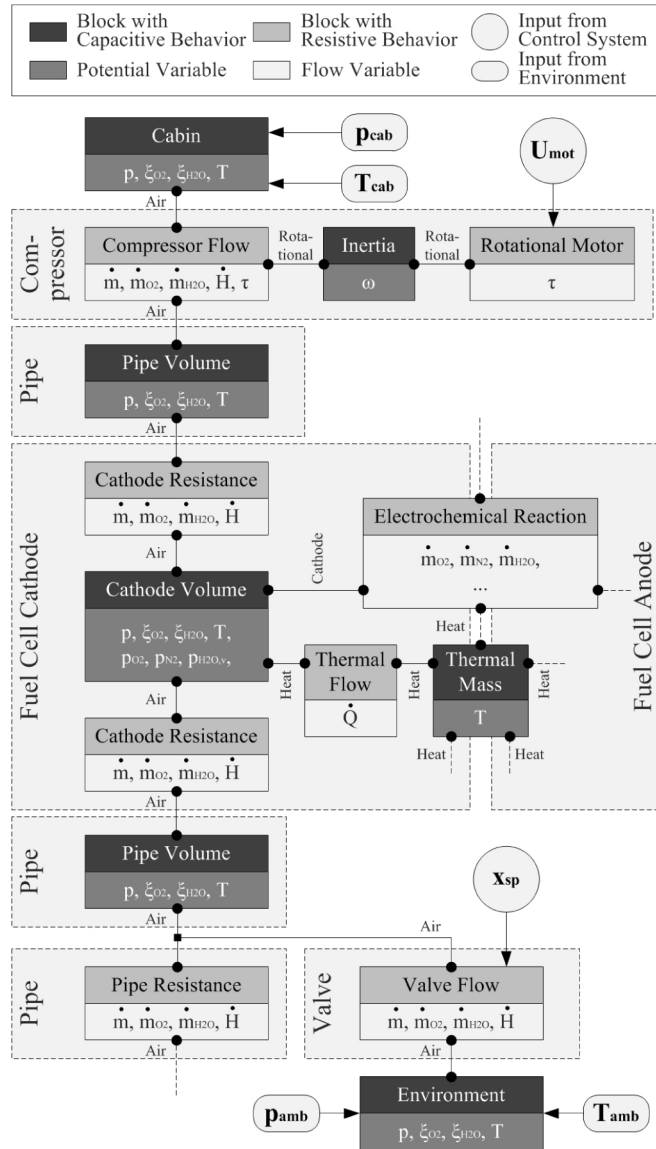


Figure 7. Model structure of air supply with fuel cell cathode

Compressor model

The compressor model includes three blocks, which represent the air flow forced by the compressor, the overall inertia and the required torque of the motor. The mass flow is computed by [19]

$$\dot{m}_{air} = V_D \cdot \phi \cdot \rho_{air,in} \cdot \omega \quad (6)$$

with the volumetric parameter V_D , the compressor map coefficient $\phi = f(p_{air,in}, p_{air,out}, T_{air,in}, \omega)$, the density ρ and the angular velocity ω . The mass flow of oxygen and water are calculated by the equation

$$\dot{m}_i = \xi_{i,in} \cdot \dot{m}_{air} \quad \text{with } i \in \{O_2, H_2O\} \quad (7)$$

where ξ_i are the corresponding mass fractions. The enthalpy flows of the compressor are determined using the equations

$$\dot{H}_{air,in} = \dot{m}_{air} \cdot c_{mix} \cdot (T_{air,in} - T_0) \quad (8)$$

$$\dot{H}_{air,out} = \dot{m}_{air} \cdot c_{mix} \cdot (T_{air,out} - T_0) \quad (9)$$

with the specific heat capacity of the gas mixture c_{mix} . The torque required to drive the compressor is computed by [19]

$$\tau_{cp} = V_D \cdot \phi \cdot \rho_{air,in} \cdot c_{mix} \cdot \frac{T_{air,in}}{\eta_{cp}} \cdot \left[\left(\frac{p_{air,out}}{p_{air,in}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (10)$$

considering the efficiency of the compressor η_{cp} . The time derivative of the angular velocity is given by

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot (\tau_{mot} - \tau_{cp}) \quad (11)$$

where J is the combined inertia of the compressor, shaft and motor. The motor torque is computed using the equation [19]

$$\tau_{mot} = \frac{\eta_{mot} \cdot k_t}{R_{mot}} \cdot (U_{mot} - k_v \cdot \omega) \quad (12)$$

with the motor parameters k_t , k_v and R_{mot} as well as the motor efficiency η_{mot} and the motor input voltage U_{mot} .

Pipe model

A pipe model can contain two different blocks depending on the type of connected components. If the neighboring blocks have resistive behavior the capacitive behavior of a pipe has to be implemented by using the pipe volume. Otherwise, the resistive behavior of a pipe has to be considered by using the flow resistance.

A pipe volume contains a certain mass of nitrogen, oxygen and water vapor. The time derivatives of the contained masses are calculated using the mass balances

$$\frac{dm_i}{dt} = \dot{m}_{i,in} - \dot{m}_{i,out} \quad \text{with } i \in \{O_2, H_2O\} \quad (13)$$

$$\frac{dm_{N_2}}{dt} = (\dot{m}_{air,in} - \dot{m}_{air,out}) - (\dot{m}_{O_2,in} - \dot{m}_{O_2,out}) \dots - (\dot{m}_{H_2O,in} - \dot{m}_{H_2O,out}) \quad (14)$$

The overall mass in the volume results from the equation

$$\dot{m}_{air} = \dot{m}_{O_2} + \dot{m}_{H_2O} + \dot{m}_{N_2} \quad (15)$$

The partial pressures are computed by