

A Model-Based Development Approach for a Diagnostic System for a Multifunctional Fuel Cell System

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ABSTRACT

In the paper at hand a model-based development approach for a diagnostic system for a multifunctional fuel cell system architecture will be presented. The approach consists primarily of four parts. The first part is a description of general steps needed to build an accurate component-based model of the system using a state of the art model-based diagnostic reasoning tool. As a first result there will be a static simulation model for nominal system behavior. The second part of the approach deals with the identification of safety critical failure conditions (SCFC) at a system level, e.g. low Power. The SCFCs are then mapped into the model. This means that categorized physical quantities and monitoring executives are chosen, that are appropriate for representing the specific SCFCs, e.g. low voltage at outlet of DC-DC converter module. According to step two there will be conflicts, meaning discrepancies between the simulated nominal and the mapped behavior. Using constraint suspension techniques for solving conflicts according to *Hamscher* and *De Kleer* [5], cause-effect relationships between SCFCs at a system level and suspected components are obtained and presented as diagnostic rules. In part three it is shown how to include those diagnostic rules into a flexible knowledge base of an expert system. The expert system is part of an online diagnostic system, whose capabilities will be illustrated in part four. This is done using a virtual test-bench for a given fuel cell system architecture. This test-bench includes possibilities to simulate faulty behavior. Finally the overall model-based development process is summed up and results are discussed.

INTRODUCTION

The increasing scarcity of resources and growing demands on the European aviation industry's social, economical and environmental impact have led to the formation of scenarios and goals for the years 2020 [1] and 2050 [2]. To face challenges like long term competitiveness, performance and sustainability new approaches and tools for a multi-disciplinary design process are demanded. On the one hand these techniques are needed to maintain and extend the European aviation's industry global market position. On the other hand these techniques are to be applied to develop and handle new technologies to make a move towards more sustainable drive trains and energy supply systems that are required for the reduction of noise and greenhouse gas emissions. On the technological side a promising approach consists in the integration of fuel cell technology into future aircraft generations. By that a major contribution in reduction of the carbon footprint of the aviation industry as well as an explicit reduction of noise emission could be achieved. Despite the ecological advantages there exist weight penalties. In order to overcome this major aeronautical drawback and guarantee also economical stimulation, the integration of fuel cell technology has to be done multifunctionally. This means that all products of the electrochemical process have to be used, so that the fuel cell (FC) does not only deliver electrical power, but also oxygen depleted air for tank inerting and fire suppression, as well as water [3]. An exemplified integration into aircraft architecture is shown in [Figure 1](#). There are displayed components and use cases for different products of fuel cell technology on board a conventional aircraft such as an Airbus A320. Technical details about the integration are not in the scope of this paper. For more information on this topic please refer to [3] and [14].

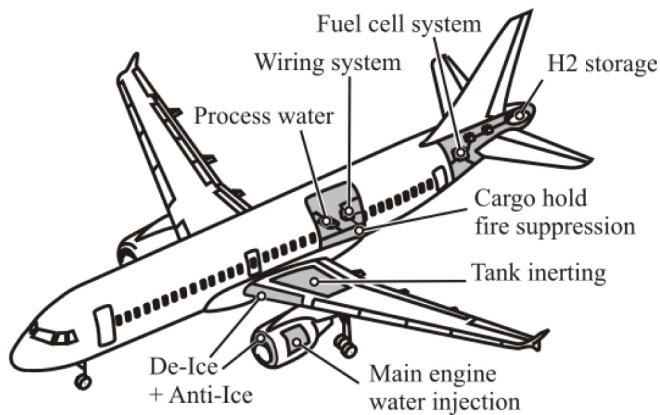


Figure 1. Introduction of fuel cell technology into the overall aircraft systems architecture.

In the paper at hand a new model-based development approach for a diagnostic system for a multifunctional fuel cell system is shown. This approach addresses two points of the vision for the year 2050. The first one is a methodology for a multi-disciplinary design process for diagnostic systems. The second point is the application of the approach to a politically and social economically demanded complex technology.

In the first part of the paper the motivation for a new model-based development approach for diagnostic systems is explained briefly. In the next part there is the methodology described in a general way. Steps and information are shown, that are needed to build a model of the system under investigation that can be used for system diagnosis purposes. Afterwards safety-critical failure conditions at a system level are identified that are to be detected and isolated during system operation. Those failure conditions are then mapped into the model. By doing so, there will be conflicts, meaning discrepancies between nominal system behavior and the mapped faulty behavior. These conflicts are being solved using graph based approaches and constraint suspension techniques, so that cause-effect relationships in form of diagnostic rules are obtained. In part three it is shown how to use these rules in building an online diagnostic system (DS). Finally the functionality of the DS is illustrated by means of a virtual test bench. All steps are demonstrated using a given FC system architecture.

MOTIVATION

During system operation there is a clear and distinct need to detect system failures and to isolate potential causes as fast as possible in order to avoid economical, as well as ecological damage. This action can be supported by means of diagnostic systems that take over those functions. In a traditional way the development of diagnostic tasks and functions is considered to be one of the last actions during system development. The growing complexity and electrification on

the technical side as well as the importance of lowering maintenance costs and system downtime on the operational side demand a closer integration of the diagnostic topic throughout the entire system development process though.

In a current industrial process diagnostic capabilities on system level are developed most often manually. A method to support this process is the failure mode and effects analysis (FMEA). In this bottom up approach faults on component level and their characteristic effects at a system level are analyzed. To gain diagnostic knowledge these cause-effect relationships have to be inverted afterwards to obtain correlations between observable physical quantities and underlying faults. Prerequisites for this approach are the possibility to identify component faults and to propagate the effects through the system. Another approach would be to use experience based knowledge, meaning observed system failure and executed maintenance actions to use this knowledge in cases when similar failures occur. The FC system architecture however is highly complex and still in early development phases, which drastically limits both known approaches.

For the mentioned reasons a new methodology is proposed, which enables the system engineer to analyze and evaluate different sensor configurations with the possibilities to gain diagnostic knowledge already in early development phases in a model-based way. Changes to the system architecture could be handled effectively and the development of the diagnostic system could be performed in parallel to trade-offs with the system development. By means of this general approach development and maintenance costs should be drastically lowered, so that one aspect for the efficient integration of FC technology into the aircraft is gained. In the following all steps of the proposed approach are shown exemplary.

A MODEL-BASED METHODOLOGY FOR THE DEVELOPMENT OF DIAGNOSTIC SYSTEMS

In the following a model-based approach for the development of diagnostic systems is described that has been applied to a multifunctional FC system (MFFCS). In its core it is a general approach that could further be used for other complex system architectures that manually are not handled in an efficient way.

PART 1 - DIAGNOSTIC MODEL

The proposed approach is based on an a-causal component-based model of the system under investigation. This model is built-up of different layers that are displayed in [Figure 2](#) and are described in the following.

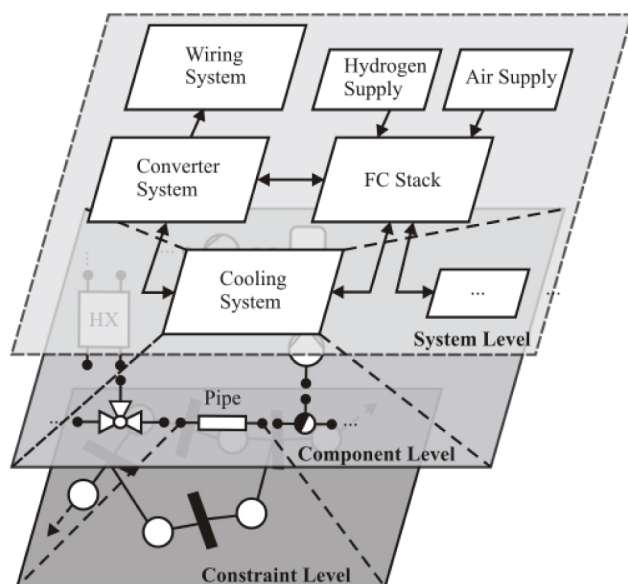


Figure 2. Hierarchical modeling approach for a diagnostic system model.

The Top-Layer of the overall model is the system level. This displays the interaction of all involved subsystems, as well as interfaces to other systems. In case of the MFFCS a hydrogen supply system and a cooling system are subsystems among others. Each of these subsystems is built-up of components, which are displayed at the component level. For the cooling system pipes and valves are typical components. On the lowest layer, namely the constraint level, the specific component behavior is defined. This behavior is stated in the form of constraints, which define relations between variables and parameters in nominal, as well as faulty cases. Included in the hierarchical modeling process for the overall system model, a multi-step approach for the definition of component behavior has been chosen. An example for that is given in the following.

To illustrate the general approach of modeling components in a constraint based way for system diagnosis according to the proposed methodology, a pressure reducer is regarded. The main purpose of this part of the hydrogen supply subsystem is to reduce the supply pressure to an acceptable level in order to protect the sensitive fuel cell membranes from high pressure loads. In Figure 3 there is the modeling approach for the component behavior displayed in a generic way. This approach consists of four steps, adapting the general modeling paradigm, stated in [4].

In Step 1 of the modeling process all the interfaces have to be defined. For components of the hydrogen supply subsystem this means that a hydrogen mass flow will be exchanged. Other information that are exchanged are potential variables, like temperature, pressure and specific data for control and monitoring. After having defined all interfaces there will be a model-shell.

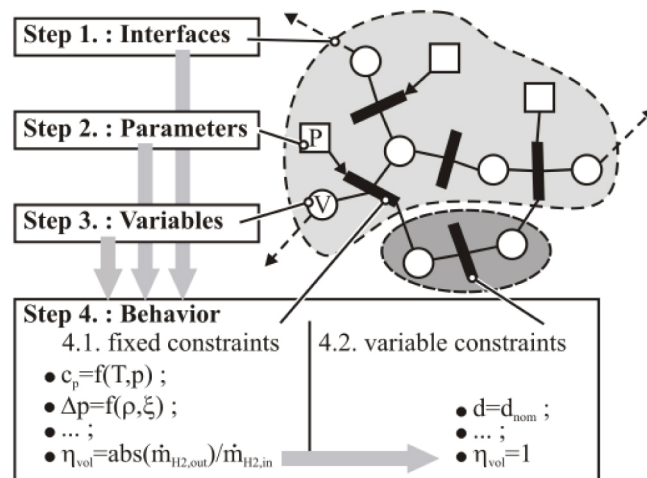


Figure 3. Multi-step modeling approach for component models.

In Step 2 all needed parameters will be added to the shell. In case of components of the hydrogen supply parameters could be length, diameter, as well as specific fixed material data. In Step 3 all the needed variables are to be defined, e.g. the pressure difference. An important aspect at Step 3 is that a restriction on values for specific variables could be needed to preclude absurd diagnostic results later on. An example for this aspect could be the pressure difference. In any case, nominal or faulty behavior, this difference, defined as difference between input and output pressure, could not be less than zero. Otherwise there would be a pressure rise over the specific component, which is physically not possible in this particular case. This point leads to Step 4 that includes the definition of behavior. As it can be seen in Figure 3 the behavioral section is divided into two parts, namely a part of fixed constraints and a part for constraints that are to be varied during diagnosis according to the *General Diagnostic Engine* (GDE) [5], which will be introduced later on. Fixed constraints are those relations between variables and parameters that are considered to be invariant both in nominal and faulty state. Examples are constraints for pressure loss over a pipe, look up tables or the definition of efficiency factors. To be varied are on the opposite constraints like the efficiency factor itself, diameters or the number of cells of a fuel cell stack.

The illustrated approach for modeling component behavior has been chosen, because it was not intended to diagnose specific component fault modes, like leakage of a pipe, mechanical damage of a gear or pinion. It was considered to be sufficient to identify defect line replaceable units (LRUs). On the one hand it is therefore not needed to know what exactly went wrong inside the component if it just has to be replaced. On the other hand specifically in case of