The Integrated Vehicle Health Management Development Process: Verification and Validation of Simulation Models

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This paper describes an end-to-end Integrated Vehicle Health Management (IVHM) development process with a strong emphasis on the verification and validation of simulation models constructed during its implementation. The simulations are both physical and functional representations of the complex system being considered. The paper proposes guidelines in developing the appropriate functional model, followed by a novel technique in which the qualitative information captured in the functional representation is verified and validated against the quantitative information offered by the physical model of the same system. Further, both physical and functional models are verified by comparison with rig data. This verification and validation process enables the development of an automated Functional FMECA (Failure Modes Effects and Criticality Analysis) by systematically capturing all the effects of the considered failure modes on the rest of the system components. The concepts engaged in this process are demonstrated on a laboratory UAV fuel delivery system test rig, but they have the ability to be further applied to both new and legacy hi-tech high-value systems.

1. Introduction

The last decade proved that the model-based approach is a solid approach in the development of Integrated Vehicle Health Management (IVHM) capabilities for high-tech high-value assets. Significant effort in physical experimentation and health system debugging are typically needed after the first asset is manufactured, leading to programme delays and additional costs. The aim of this paper is to highlight the steps that allow the verification and validation of the health management conceptual design before the implementation phase is initiated. The constructive approach adopted here (verification and validation throughout the entire process) keeps the development efforts synchronized with system-engineering additions and modifications.

1.1 Problem statement

Here, a UAV fuel delivery system is selected to demonstrate the IVHM development process. Five failure modes affecting five different components were selected for the demonstration of the challenges and opportunities when employing a mix of quantitative and qualitative representations of the system for development of an IVHM solution. The small scale fuel system test bed is an adaptation of the DEMON UAV (Fielding et al., 2010) fuel delivery system and is shown in Figure 1. It consists of two tanks (one main tank and a sump tank (which emulates the virtual engine)), a gear pump, a set of valves and the associated tubing that connects all the components together and enables the implementation of an engine feed scenario. The components affected by a single failure mode are: the filter, the gear pump, the shut-off valve, one of the pipes and the nozzle. The failure modes are grouped and labelled as in Table 1. As a small number of failure modes are considered, the goal is to develop a health management solution that is able to detect a malfunction in the system, but also to discriminate between all five faults under various operating conditions. Therefore, 100 % Fault Detection and Isolation (FDI) indicators and no ambiguity groups are specified as the requirements.

Figure 1: Fuel system test rig

Table 1: Components and failure modes considered for the IVHM analysis

Component	Failure mode	Label
Filter	Clogged	FM1
Pump	Degraded gear	FM2
Shut-off valve	Stuck mid-range	FM3
Pipe	Leaking	FM4
Nozzle	Clogged	FM5

Two simulation models were independently constructed for development of an IVHM solution capable of detecting and isolating the five failure modes. These models are capable of representing the system from two different perspectives: a physics-based and a functional perspective. Simulation techniques using such approaches are already in use during the development process of high-value assets: physics-based models are developed during the design cycle of a new product and the functional perspective is considered during the development of Failure Mode Effects and Criticality Analyses (FMECAs). The first type of model is usually verified and validated against existing data from previous products and the first prototype version of the new system. The function-based type of analysis lacks systematic verification and validation as it is a more subjective task. The FMECA is carried out as a group based activity, subject to engineers' individual experience and the novelty of the proposed physical-functional approach is represented by the fact that it allows the incorporation of a systematic method for identification of the critical components and their impact on the overall system functionality. This approach enables the systematic construction of physics-based quantitative and functional-based qualitative models that are an accurate representation of the real product. These models are further used for the development and the implementation of the health management solution throughout Functional FMECAs (FFMECAs) (Rudov-Clark, 2009).

Section 2 describes in detail the health management process. Section 3 highlights the development of the main two pillars of this approach: the physical simulation and the functional decomposition of a complex system. Section 4 describes the verification and validation steps in correlating quantitative and qualitative information describing the same system and section 5 contains the concluding remarks in addition to the lessons learnt when using this approach.

2. Health Management Development Process

The health management development process adopted here is a new approach meant to combine in a systematic manner the physical and functional dimensions of a complex system allowing the development of an IVHM solution based on the knowledge encapsulated by these two dimensions A mix of physical information regarding each of the system' components is analyzed against the designed functionality of those particular components by systematically capturing the failure mechanisms of the functional failure of those respective components. The approach contains seven individual layers and they have been detailed in (Niculita et al., 2013). These seven layers are highlighted in Figure 2. Within the analytical framework of this process the development of the health management solution was synchronised with the development of physical conceptual design and the functional conceptual design of the real asset. Various health management solutions are further enhanced throughout the detail design and implementation phases until the final deployment of the asset in service.
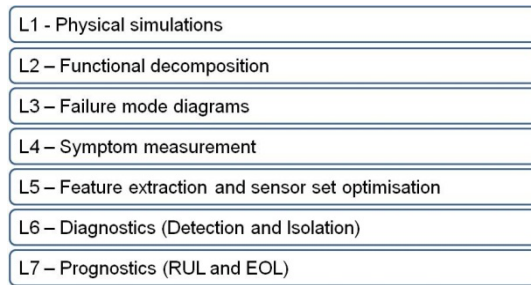
| L1 - Physical simulations |
| L2 – Functional decomposition |
| L3 – Failure mode diagrams |
| L4 – Symptom measurement |
| L5 – Feature extraction and sensor set optimisation |
| L6 – Diagnostics (Detection and Isolation) |
| L7 – Prognostics (RUL and EOL) |

Figure 2: IVHM Analytical Framework

The top two layers of the analytical framework (L1 and L2) encapsulate the development of the two main pillars of the process:

i.   The physical simulations contain quantitative information regarding system behaviour under healthy and faulty conditions

ii.   The functional representations contain qualitative information describing the normal and abnormal functionality of the same system.

These two layers are complemented by a functional failure propagation model (layer L3) that includes failure diagrams associated to each failure mode. Each failure diagram contains cause(s), mechanism(s), fault(s), potential symptom(s) and the link between the fault to the functional failure that determines a change in system behaviour. Layer 4 and layer 5 address the identification, optimisation and further enhancements of the sensing solution capable of detecting and isolating the functional failures considered under the diagnostic and prognostic analysis. Each of the failure modes has a specific impact on all or some of the parameters describing the system. The intensity of the impact was previously captured and documented by the physical and functional system's representation; therefore it is required to create a perfect correlation between the quantitative and qualitative information in order to generate sensing solutions that are capable of supporting the health management capability for diagnostics and prognostics purposes (layers 6 and 7). The problem addressed by this paper is the elimination of the delays in the development program schedule generated by the misrepresentations of the system using functional approach. The verification and validation process suggested here highlights the fact that physical and functional models cannot be constructed in isolation, and since the physical models are developed by the system designers and functional representations and functional failure models are generally constructed by the health management designers, a continue dialog between these two parties is mandatory throughout the development process of the asset. An additional requirement for the implementation of this IVHM process was to use strictly commercial-of-the-shelf (COTS) software tools. Physical dimensions of a system can be captured by a wide palette of software tools available on the market. At the moment, there aren't many software packages that allow the development in a systematic manner of functional models for complex system in order to identify sensing solutions capable of highlighting system functional failures. MADe™ software produced by PHM Technology is a good example for diagnostic software that supports such tasks. It also allows four different departments of an organisation (system designers, reliability-availability-maintainability (RAM), prognostic and health management engineers (PHM), support-logistics-maintenance technicians to use and update one single system model, enabling the dialog previously mentioned.

3. Physics-based and function-based system representations

Physical models of various complexities are generally used at different design stages of a new system. They are mainly developed to carry out trade studies in sizing and selecting correctly the components in order to meet the original specifications of the system. For the UAV fuel delivery system, such model was developed using multi-domain simulation package SimulationX™ from ITI. A snapshot of the test rig physical model developed using this tool is depicted in Figure 3.
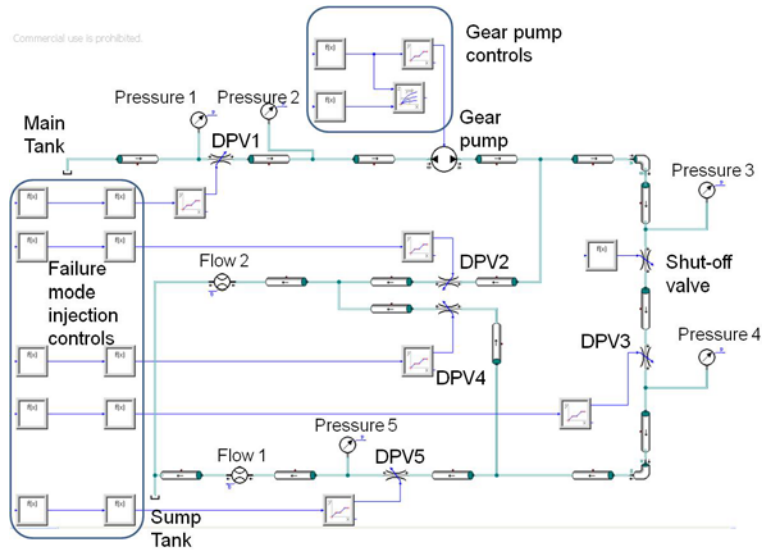
Figure 3: SimulationX™ fuel system physical model

The verification and validation of this particular physical model was to some extent built-in within the construction of the model itself. Since the majority of the components were low cost type of components, characterisation data from the manufacturers was not available, therefore it had to be determined step-by-step and attached to the model. In this manner, pump characteristics map was obtained by measuring the pressure rise across the pump, for various pump speed and various volumetric flow rates. Following the same approach, pressure drop/flow rates across shut-off valve and the loss coefficients curves versus valve opening for the direct acting proportional valves (DPV) were identified for various operating conditions. Once the entire fuel delivery system model was completed, data generated by the model were compared to the data obtained from measurements on the test rig for various mission profiles (e.g. taxi - take-off – cruise – landing - taxi). The error margins generated by the V&V process will be further discussed in section 4.

System functionality is usually captured during the conceptual design phase of a new system. Within the second phase of the analytical framework (L2), the functional model encapsulates a functional decomposition of the entire system down to individual components (Figure 4). In order to undertake the functional decomposition task, a COTS software tool was employed and this software was MADe™ software. The concepts underpinned this software and the guidelines for the construction of a functional model are described in a previous study (Niculita et al., 2012). The functions of each individual component of the fuel delivery system are marked with red in Figure 4. The functional decomposition of a complex system allows the prognostic and health management designer to identify and optimise the features that are signalling a deviation outside the designed function of a components/system (e.g. a pump is designed *to supply* a specific amount of volumetric flow rate for a specific load and a specific rotational speed value; when the volumetric flow rate is below the expected designed value, it can be considered that the pump is not operating correctly therefore its function is affected by a fault)(Figure 5). In this manner, we aim to identify the functional failure of a component/system by interrogating the functional output flow (in the previous case of the pump the functional output flow is the volumetric flow rate). Within the health management development process from Figure 2, the functional decomposition (L2) is complemented by the identification of failure diagrams (causes-mechanisms-faults-functional failures) in order to develop a functional FMECA at the component/system level (L3). The failure diagram can be defined only for particular components (that are intended to be monitored) or it can be defined for all components and subsequently, a threshold should be set based on the Risk Priority Number (RPN) in order to narrow down the analysis strictly to the most critical components. The main advantage of the MADe™ package is that by using the FFMECA as a baseline, the software enables the identification and optimisation of various sensor set solutions that are capable of detecting and isolating the functional failures associated to specific components.
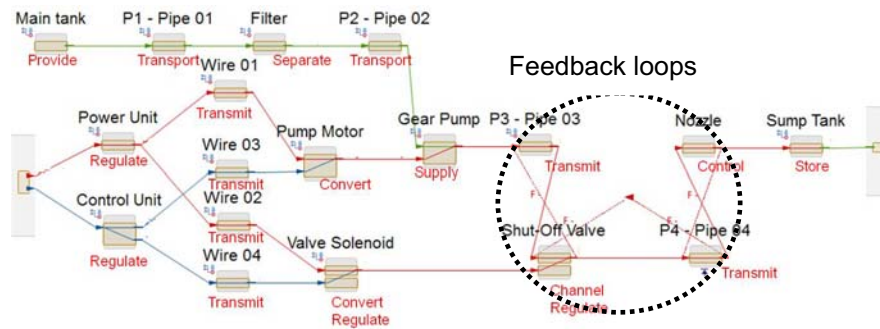
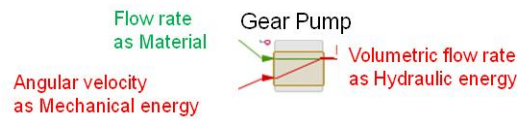Figure 4: MADe™ fuel system functional model – a system level decomposition view

Figure 5: MADe™ gear pump functional model – input/output flows

As the process of sensor identification is based on the traditional failure modes effects and criticality analyses studies developed from a functional perspective, our challenge was to align functional models to the physical representation of the systems that were described at the beginning of this section.

4. Verification and validation of IVHM models

This section will discuss the verification and validation of physical and functional models constructed throughout the health management development process. The V&V of the physical model was carried out by comparing the results obtained from simulations of various operating conditions to the data obtained through measurements on the test rig. As the model doesn't take into account the variations of atmospheric pressure and temperature, differences quantified as being less that 3% between the various parameters generated by the model (volumetric flow rates and pressures at different locations) and the test rig were considered to be satisfactory for the initial stage of the project. The degradation curve associated to the clogged filter scenario is depicted in Figure 6 where every 30 seconds segment represents a different degradation phase of the gradual clogging phenomenon. Similar correlation was obtained in the other four faulty cases (degraded gear pump, shut-off valve stuck mid range position, leaking pipe and clogged nozzle).
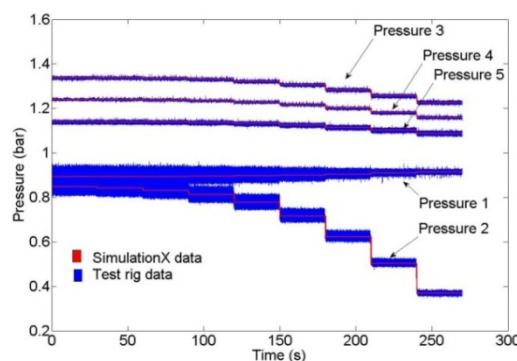

Figure 6: Validation of physical models with reference to the real system – clogged filter scenario

Opposite to the construction of physical models (using quantitative discrete information), the development of functional models involves a higher degree of subjectivism as it involves the use of qualitative concepts. Throughout the development of such models, various versions of the same model of the UAV fuel system using MADe™ software have been generated. All of them were validated by the completion verification mechanism (within the tool –e.g. no missing connections, input/output flow compatibility between

components) but there is still the question whether or not they do represent the fuel system under investigation. The main advantage of having layers L2 and L3 coupled together within the same model (the functional decomposition and the failure diagrams representation) is that a fault propagation table can be generated. The table contains the effects of the considered failure modes on the rest of the components (upstream and downstream throughout the entire system) (Figure 7). Each row of the propagation table represents the description of the effects associated to a specific failure mode *FM*i on the functional output flows of the others system' components (P_i to P_j) using qualitative indicators (*Low* or *High*). The same indicators could be extrapolated from the physical model by simulating the degradation phenomenon of each individual failure mode from a quantitative perspective. As the physical models contain the ground truth information about a system, a valid functional model should generate the same indicators $x_{i,j}$ for each individual row corresponding to a failure mode that was considered for the analysis.
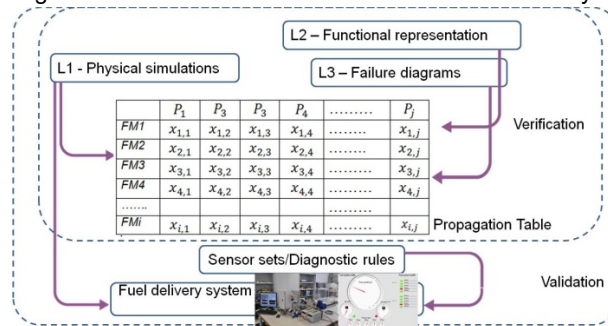

Figure 7: Verification and validation of functional models with reference to physical simulations

Throughout the verification phase, iterations of the functional models should be carried out until a propagation table similar to the one generated by the physical models is obtained. Typically, such iterations include the addition of feedback loops, identical to the ones highlighted in Figure 4. These are based on the fact that particular failure modes have bi-directional effects (downstream but also upstream) throughout the rest of the system. In the case of a clogged nozzle (Figure 4), less flow will be generated after this component (as an effect of the clogging); therefore more flow is forced into pipe 04, triggering the increase in the pressure parameter in this part of the tubing. This was obtained by linking a negative feedback loop between the output flow of the nozzle and the input flow of the pipe 04. The validation phase also involves the testing of the sensor set solution/diagnostic rules on the real asset (identified using functional analysis) by interrogating the model of normality (given by the physics-based simulation) as in Figure 7.

5. Concluding remarks

A physical and functional model of an UAV fuel delivery system were developed using SimulationX™ and MADe™ software tools and a series of IVHM analyses were carried out during this work. While modeling the fuel delivery system using this physical-functional approach a number of lessons have been learnt, specifically: 1) Care must be taken in setting up the functional model with the choice of component functions and inflow/outflow to these functions, 2) The functional taxonomy has to be very well understood and accepted by the user, 3) Functional-based and physics-based simulations cannot be done in isolation, 4) The functional approach requires permanent contact with the output of the physical simulation in order to be able to develop a model that will accurately represent the real system.

References

Fielding J.P., Lawson C.P., Pires R.M, 2010, Development of the Demon Technology Demonstrator UAV, Paper 271 27th ICAS Congres.

Niculita O., Irving P., Jennions I.K., 2012, Use of COTS functional analysis software as an IVHM Design Tool for Detection and Isolation of UAV Fuel System Faults, Proceedings of the Conference of the Prognostics and Health Management Society, Minneapolis, paper #105.

Niculita O., Jennions I.K., Irving P., 2013, Design for Diagnostics and Prognostics: A Physical-Functional Approach, Proceedings of the IEEE Aerospace Conference, BigSky Montana, paper # 2393.

Rudov C., Stecki C., Stecki, J., 2009, The language of FMEA: on the effective use and reuse of FMEA data, Sixth DSTO International Conference on Health & Usage Monitoring.