Towards an Integrated COTS Toolset for IVHM Design

Octavian Niculita[1], Ian K Jennions[2], and Miguel Medina Valdez[3]

[1,2] *Integrated Vehicle Health Management Centre, Cranfield University, Cranfield, Bedford MK43 0AL, UK*
[3]*Cranfield University, Cranfield, Bedford MK43 0AL, UK*

o.niculita@cranfield.ac.uk
i.jennions@cranfield.ac.uk
miguel.medina@cranfield.ac.uk

ABSTRACT

This paper describes an end-to-end Integrated Vehicle Health Management (IVHM) development process with a strong emphasis on the automation in creating functional models from 3D Computer Aided Design (CAD) system's representation, throughout the implementation of this process. It has been demonstrated that functional analysis enhances the design and development of IVHM but this approach is not widely adopted by industry and the research community as it carries a significant amount of subjectivism. This paper is meant to be a guideline that supports the correctness through construction of a functional representation for a complex mechatronic system. The knowledge encapsulated in the 3D CATIA™ System Design environment was linked with the Maintenance Aware Design environment (MADe™) with the scope of automatically creating functional models of the geometry of a system. The entire process is documented step by step and it is demonstrated on a laboratory fuel system test rig. The paper is part of a larger effort towards an integrated COTS toolset for IVHM design. Another objective of the study is to identify the relations between the different types of knowledge supporting the health management development process when used together with the spatial and functional dimensions of an asset. The conclusion of this work is that a 3D CAD model containing the topological representation of a complex system can automate the development of the functional model of such a system.

1. INTRODUCTION

Functional Modeling is a System Engineering discipline typically carried out in the conceptual design phase of an asset. The main goal of the functional modelling is to capture, as early as possible, the overall main function of the system as well as the function of each individual component of this system. Complex systems from aerospace, off-shore, mining and maritime industry sectors change their role over the life time, and in these cases they have to meet new requirements related to cost, safety, reliability, maintainability and availability (Stecki et al., 2014). The first three types of requirements are typically specified upfront and they have been embedded into best design practices for nearly six decades. The last two types of requirements are often derived from the initial three sets of requirements as the hardware and software limitation force the designers to think of the design using one or a mix of the following three approaches:

1. Design alterations
2. Redundancy
3. Adoption of IVHM technologies

The last approach can be successfully used when the system's risks are identified in a systematic manner. Functional decomposition of a complex system, identification of critical components, Functional Failure Mode Effect and Criticality Analysis (FFMECA) are developed of the same time in order to construct a complete picture at the effects of failure models on the overall system's function. FFMECA can also act as foundation for assessment of failure mode propagation throughout system, identification and optimization of sensor set solutions, and construction of expert systems capable of detecting and isolating a given failure mode universe. Functional dimension of a system has to be backed up by the engineering knowledge expressed typically through physics-based models. An IVHM development process based on a mix of physical-functional analysis proved to offer a systematic approach in designing IVHM solutions of small scale real systems (e.g. an UAV fuel system) (Niculita, 2012). This process was instantiated using strictly COTS software tools (Niculita, 2013). One of main challenges throughout this instantiation was the construction of the functional model of the fuel system from scratch. Also, the significant amount of engineering knowledge related to the system itself that has to be readily available to the IVHM analyst when constructing its functional representation (so that this model is indeed a true representation of the real system) is another explanation for this approach not being used at a wide scale. Functional analysis was previously described in the literature as a tool to support the overall engineering design process of large-scale cyber-physical systems (Stone & Wood, 2000; Hirtz et al, 2002, Kurtoglu et al., 2008; Uckun, 2011; Komoto & Tomiyama, 2012). All these references focused on the use of functional analysis in supporting various engineering tasks throughout the design of complex systems from a healthy perspective. Although the references mentioned above point to the function-behavior-structure (FBS) triad when shaping a new design, this triad only captures the healthy state of a system. Stecki (2013) introduced MADe™ as the one of the COTS software tools capable of employing functional reasoning approach to support development of IVHM capability by taking into account the healthy and faulty states of a system. The goal of the current paper was to automate the IVHM design phase within the health management development process when using this particular tool. The main purpose of this effort was to be able to reuse the existent information regarding the structure of a system, information which is already available at different design stages of a given asset. For this purpose, we used a laboratory test rig to identify the steps of the process that allows an IVHM analyst to automatically generate the functional model from the 3D representation of such a system, representation which is typically constructed by a fuel system designer using a bespoke CAD tool. This paper employs CATIA™ to emulate the fuel system designer activity of capturing the structural layer of a system.

Compared to the previous work in functional modelling, the novel contribution of this paper can be summarized as follows:

1. A practical guide in identifying the steps an IVHM analyst has to go through to automatically generate functional models from structural models (previously created by system designers) using strictly COTS tools (CATIA™ and MADe™).
2. Enhancements required to be carried out on the functional models in order to be a truly representative qualitative dimension of the behavior quantitative models of the same system.
3. A use-case of an UAV fuel system application that highlights the main benefits of this approach in designing IVHM solutions for complex systems.

The paper is organized as follows. Section 2 describes the IVHM development process. Section 3 summarizes the CATIA™ 3D representation of the test bed as part of the system design and also of the steps of the process that automatically generates the MADe™ functional model out of 3D structural representation. The enhancements made to the functional model to be an accurate representation of the physics-based behavior model are described in Section 4. Section 5 collates the concluding remarks and a summary of the future direction of this research.

2. IVHM DEVELOPMENT PROCESS

The IVHM development process has been previously described in (Niculita, 2013). In this, a functional analysis is used (Figure 1) for the modelling of the effects of failure modes throughout the system (downstream effects but also upstream effects). The existent process will be enhanced by using the information gathered within CAD models to reduce the time and work required to create from scratch a functional representation of a given asset. Very often, physics-based models (depicted as an output of the System Design activity – first stage of the IVHM development process) do not necessarily describe the exact structure of a system. For example, if a pipe doesn't introduce a significant pressure drop, it will be easily discarded by the system modeler when constructing a physics-based model of a fuel system or of an environmental control system. In this context, construction of functional models based on design schematics of physics-based models is difficult. For this reason, we attempted to link the development of functional models to 3D CAD models as such representations capture every single component within a complex system.

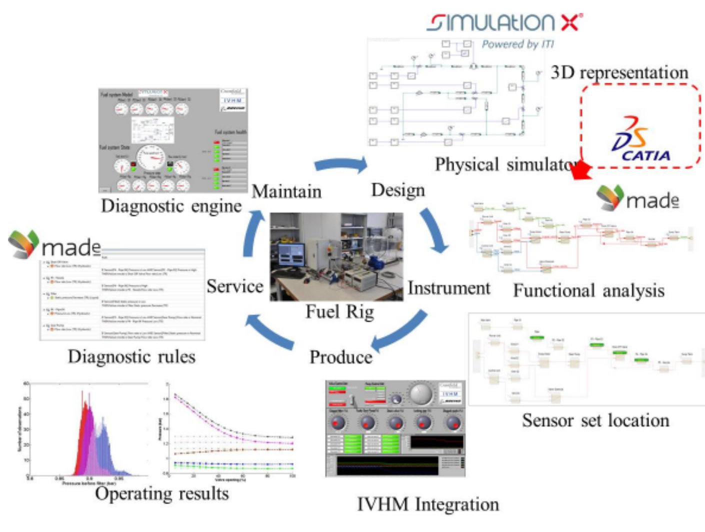


Figure 1. Health management development process.

Although the IVHM development process is mapped against the generic engineering cycle (Design, Safety and Reliability analysis, Integration, Service and Maintenance) the modelling activities supporting the IVHM Design do not necessarily take place sequentially as depicted in the above cycle. Over the last two decades, industry and academia attempted to integrate the IVHM Design into System

Design, although a clear methodology is still not available. Three dimensions in modelling a system have been identified as being capable of supporting the integration of two processes (Design and IVHM) into a common thread:

1. Functional modelling
2. Behavior modelling
3. Structure modelling

These three dimensions are complemented by the physical embodiment of a system as per Figure 2. The current paper will address the Function-Structure link and will offer a method to execute this link using COTS tools.

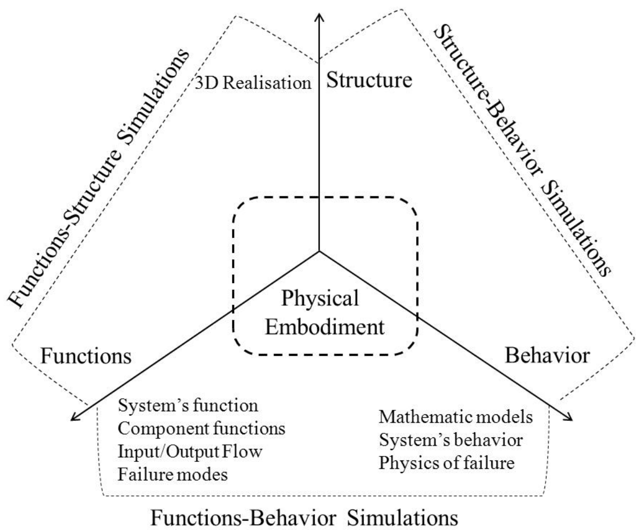


Figure 2. FBS and Physical embodiment relations

(Canedo, 2013) described the generation of multi-domain simulation models capturing both the behavior-structural dimensions of a system from the functional representation of a system that is constructed using basic elementary functions to simulation components available in Modelica (Modelica Association). This study constructs the Functional-Behavior-Structure framework from a Design perspective without introducing IVHM related concepts. Our attempt is to instantiate a generic FBS triad with the information related to system risk identification, effects of failure modes throughout the system, criticality figures in order to support Design for Availability of cyber-physical system.

3. SYSTEM DESIGN – STRUCTURE MODEL

A CAD model encapsulates a 3D representation of a given system capable of offering a digital product view.

MADe has the capability of importing CAD models to automatically create functional models from a 3D representation of an asset; this was exercised on a laboratory test-bench fuel system example and the overall step-by-step process is thoroughly described in this paper. Within this section, several findings are marked with label *Fx* in order to support future implementation of this process.

The CAD model has to be represented at the part level (*F1*); Figure 3 highlights the CAD model and its decomposition at the part level for a fuel filter component. The fuel filter selected for this fuel system (ASSY-Filter FESTO VAF-PK-3 535883) is composed of five internal parts/elements: indicator, filter head, o-ring seal, filter element, filter housing.

All these part have to be represented in CATIA in order to allow MADe to correctly import this particular component. The same level of detail has been employed for the representation of the entire fuel system test rig. At the end of the design process, after modelling and assembling components, a final assembly emerges. Figure 4 shows the CATIA Final ASSY of the fuel system test bed subject to study.

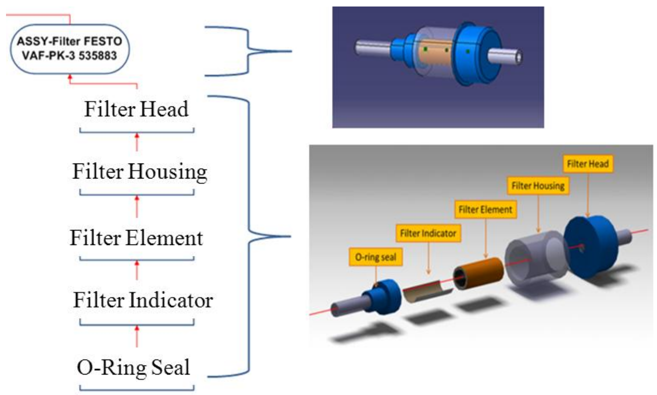


Figure 3. CAD model of the fuel filter.

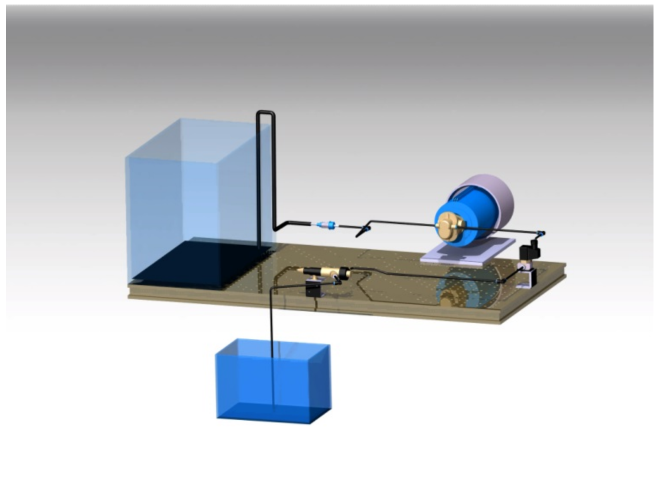


Figure 4. CAD model of the fuel system.

In order to exchange this information to business partners, supply chain or contractors, it is necessary to generate a file in a neutral computer interpretable representation of system data. The International Organization for Standardization generated the ISO 10303 standard that can support this task. (SCRA Advanced Technology Institute, 2006) discusses in their publication STEP Application Handbook the current state of art in generating STEP files and their usability in the industry by CAD, CAM and CAE systems. Also, they highlight the importance of maintaining and updating the information when exchanged among different users/departments of large organization. The main advantage of the STEP file format is the fact that it can be used by other software platforms to exchange information. CATIA software automatically generates this *.stp file from a CAD model using the ISO-10303-21 standard.

Figure 5 highlights a part of the STEP code that was generated from the CAD model for this particular system.

4. SYSTEM DESIGN – FUNCTIONAL MODEL

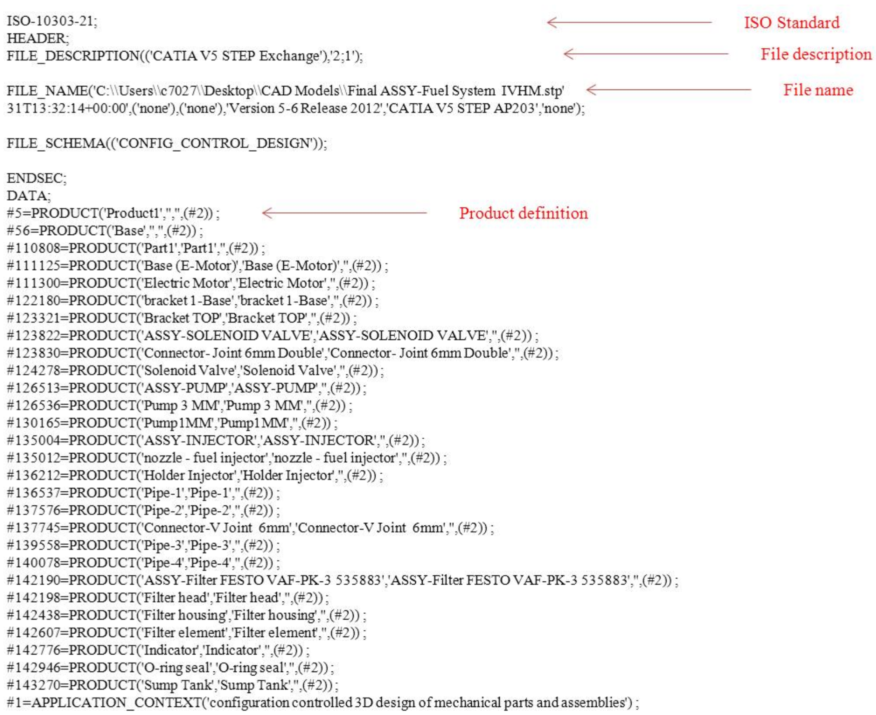
The STEP file was then imported into the MADe™ CAD interface in order to extract information contained inside the CAD solid models. This interface identifies and selects information located in the Product definition section of the STEP file. Within the next step, this information is translated it into a *.mcdx file, which is a transition format before the data characterizing a component/system is finally imported into MADe™. Figure 6 illustrates the extracted information from the CAD file that is translated into a *.mcdx file.

Pairs between components can be also created by this interface. The pairs constitute the relationships among the different parts that directly interact within a component. Assembly components are structured in a hierarchical list. This arrangement highlights the level of each component and their hierarchical position within the system under investigation.

Within this intermediate step, the MADe FMEA Interface will validate imported files against those currently available in the MADe library (a standard library or a customized library by the IVHM Team). The CAD model should use the same taxonomy as the one available within the MADe built-in component library (*F2*). If a functional model of a filter manufactured by FESTO has been previously created and saved as part of a MADe library under the name "ASSY-Filter FESTO VAF- PK-3 535883", the CAD model of the fuel system will have to carry exactly this label when this specific type of filter is used as part of the fuel system design (*F3*).

During the import process, the hierarchy of the system and all the connections between sub-systems, components, parts have to be carefully mapped by the IVHM analyst as no automated technique is currently available in MADe (*F4*).

Figure 7 depicts a flow diagram containing specific tasks that are required to be carried out in order to use the MADe CAD interface.




```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('CATIA V5 STEP Exchange'),'2;1');

FILE_NAME('C:\\\Users\\c7027\\Desktop\\CAD Models\\Final ASSY-Fuel System  IVHM.stp'
31T13:32:14+00:00',('none'),('none'),'Version 5-6 Release 2012','CATIA V5 STEP AP203','none');

FILE_SCHEMA(('CONFIG_CONTROL_DESIGN'));

ENDSEC;
DATA;
#5=PRODUCT('Product1','','',(#2)) ;
#56=PRODUCT('Base','','',(#2)) ;
#110808=PRODUCT('Part1','Part1','',(#2)) ;
#111125=PRODUCT('Base (E-Motor)','Base (E-Motor)','',(#2)) ;
#111300=PRODUCT('Electric Motor','Electric Motor','',(#2)) ;
#122180=PRODUCT('bracket 1-Base','bracket 1-Base','',(#2)) ;
#123321=PRODUCT('Bracket TOP','Bracket TOP','',(#2)) ;
#123822=PRODUCT('ASSY-SOLENOID VALVE','ASSY-SOLENOID VALVE','',(#2)) ;
#123830=PRODUCT('Connector- Joint 6mm Double','Connector- Joint 6mm Double','',(#2)) ;
#124278=PRODUCT('Solenoid Valve','Solenoid Valve','',(#2)) ;
#126513=PRODUCT('ASSY-PUMP','ASSY-PUMP','',(#2)) ;
#126536=PRODUCT('Pump 3 MM','Pump 3 MM','',(#2)) ;
#130165=PRODUCT('Pump1MM','Pump1MM','',(#2)) ;
#135004=PRODUCT('ASSY-INJECTOR','ASSY-INJECTOR','',(#2)) ;
#135012=PRODUCT('nozzle - fuel injector','nozzle - fuel injector','',(#2)) ;
#136212=PRODUCT('Holder Injector','Holder Injector','',(#2)) ;
#136537=PRODUCT('Pipe-1','Pipe-1','',(#2)) ;
#137576=PRODUCT('Pipe-2','Pipe-2','',(#2)) ;
#137745=PRODUCT('Connector-V Joint  6mm','Connector-V Joint  6mm','',(#2)) ;
#139558=PRODUCT('Pipe-3','Pipe-3','',(#2)) ;
#140078=PRODUCT('Pipe-4','Pipe-4','',(#2)) ;
#142190=PRODUCT('ASSY-Filter FESTO VAF-PK-3  535883','ASSY-Filter FESTO VAF-PK-3 535883','',(#2)) ;
#142198=PRODUCT('Filter head','Filter head','',(#2)) ;
#142438=PRODUCT('Filter housing','Filter housing','',(#2)) ;
#142607=PRODUCT('Filter element','Filter element','',(#2)) ;
#142776=PRODUCT('Indicator','Indicator','',(#2)) ;
#142946=PRODUCT('O-ring seal','O-ring seal','',(#2)) ;
#143270=PRODUCT('Sump Tank','Sump Tank','',(#2)) ;
#1=APPLICATION_CONTEXT('configuration controlled 3D design of mechanical parts and assemblies') ;
```

Figure 5. STEP File associated to the fuel system CAD Design.

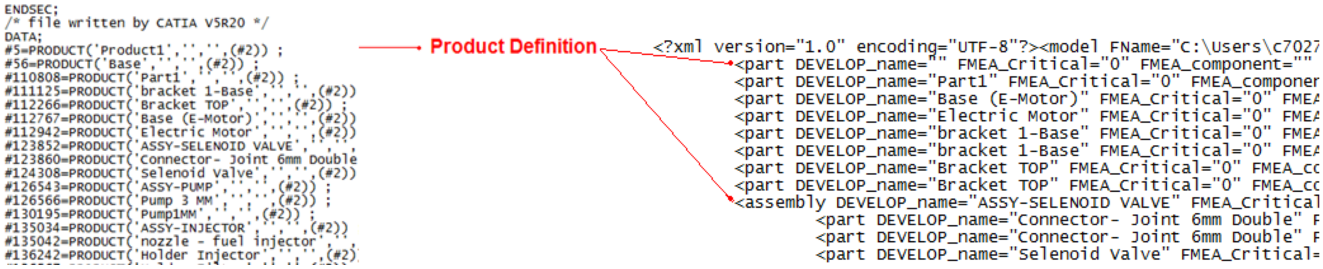


Figure 6. Component selection from product structure contained by the MCDX file.

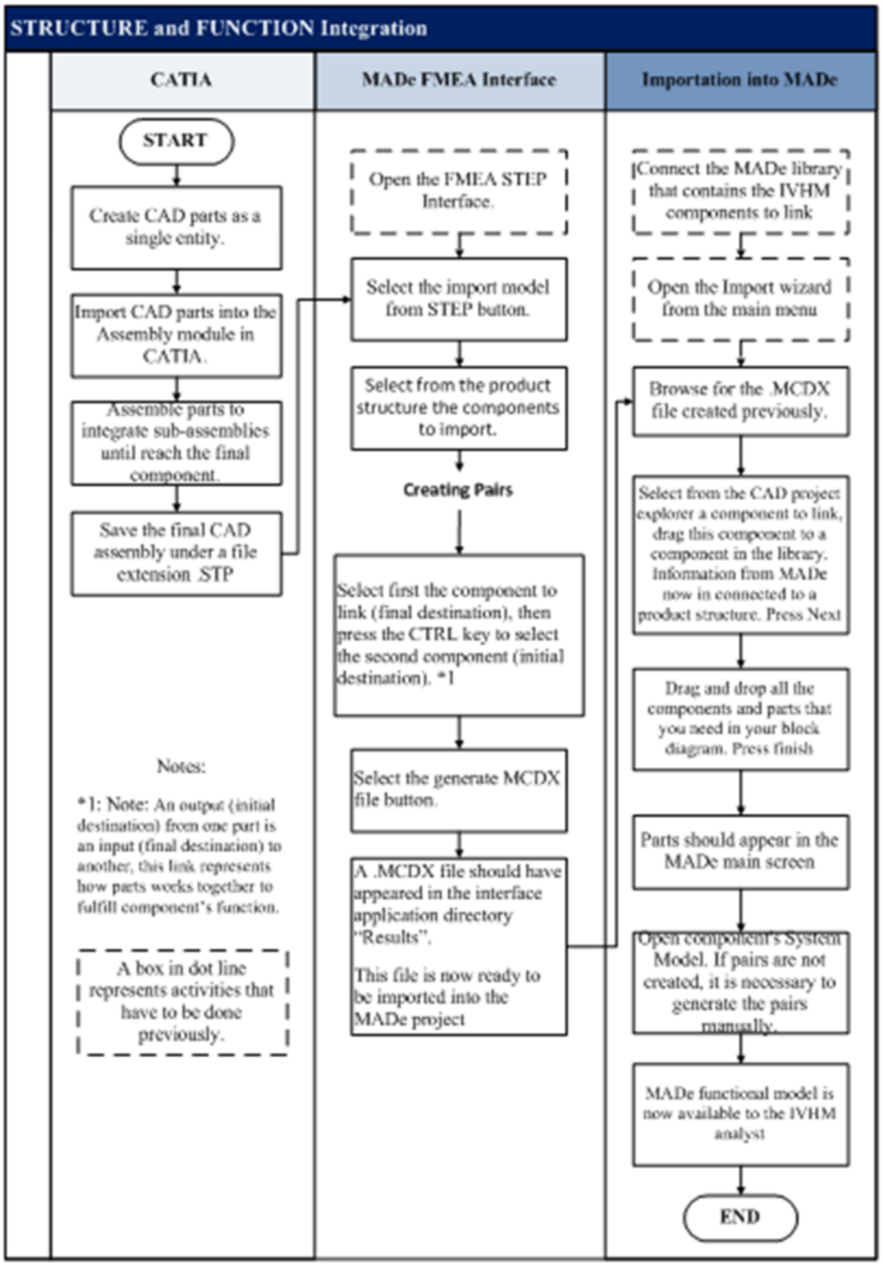


Figure 7. MADe CAD integration steps.

Following the steps described in the previous flow diagram, the functional model of each individual component of the fuel system has been created (at the part level). As an example, the figure below describes the links between the parts of the filter component which match the physical links of this particular component (e.g. the filter element is coupled to the filter head and the filter housing, each of these two couplings forming two pairs).

The translation of a CAD model into a functional model using the MADe dedicated FMEA Step tool is carried out at the component level.

The MADe CAD Interface is capable of creating pairs between parts, but this process is manually done through the CAD Interface tool (*F5*).

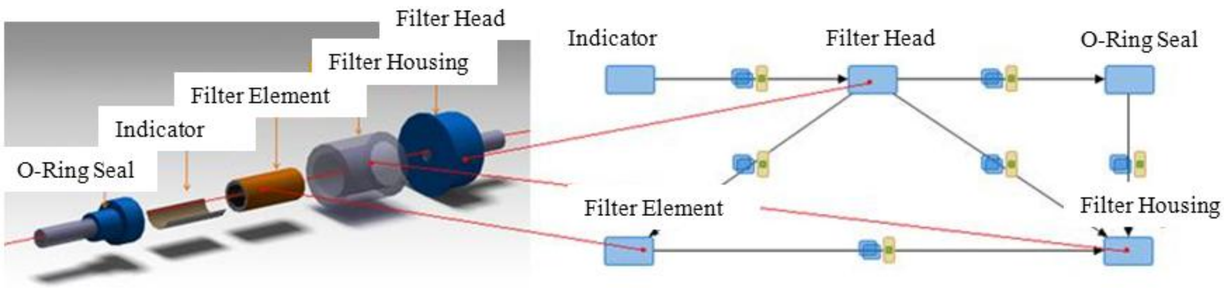


Figure 8. Translation of physical connections internal parts of a filter into the functional pairs.

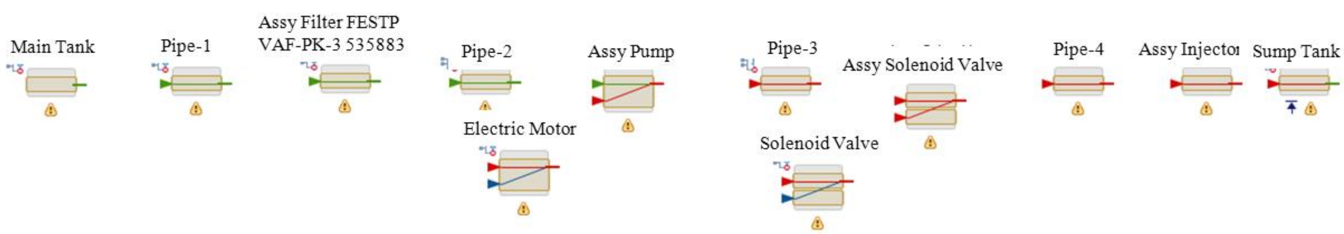


Figure 9. The fuel system functional model automatically created by the MADe CAD Interface from a CAD 3D model (hydraulic view).

Presently, there is no automatic technique for determining pairs in the MADe CAD Interface, as it is considered very difficult to determine accurately the connections between parts based primarily off the geometry of the CAD (for example, if a part was really close to another but had no actual interaction between another it would potentially make an erroneous pairing) (*F6*). Figure 9 describes the hydraulic engineer view as the CAD 3D model addressed only the hydraulic representation of the fuel system (it included the pump motor and shut-off valve solenoid). The rest of the components forming the fuel system electrics and controls have to be integrated with the CAD 3D hydraulic model in order to be automatically linked (as part of the automated process) with functional models characterizing such components. If the representations of such systems (e.g. electrical system, control system) are not available for the IVHM analyst, functional models of representative components can be used and they are manually added to the model in order to obtain a complete picture of the fuel system functional model. Figure 9 depicts a multi-dimensional view of the fuel system. Different engineering disciplines are nowadays integrated as part of the same system. The representation of this fuel system schematic in MADe software (containing the information from three different worlds - hydraulic, electrical, and controls) and it was obtained by linking the input and output flows of the components from Figure 8 and by manually adding the functional representation of power unit, control unit and different wires used to connect these units to the fuel system.

The output flows were connected with the input flows of the downstream component and an initial functional representation of the fuel system was achieved. The output of this operation is depicted in the Figure 11 as it captures the collection of functional models for all components of the fuel system test rig.

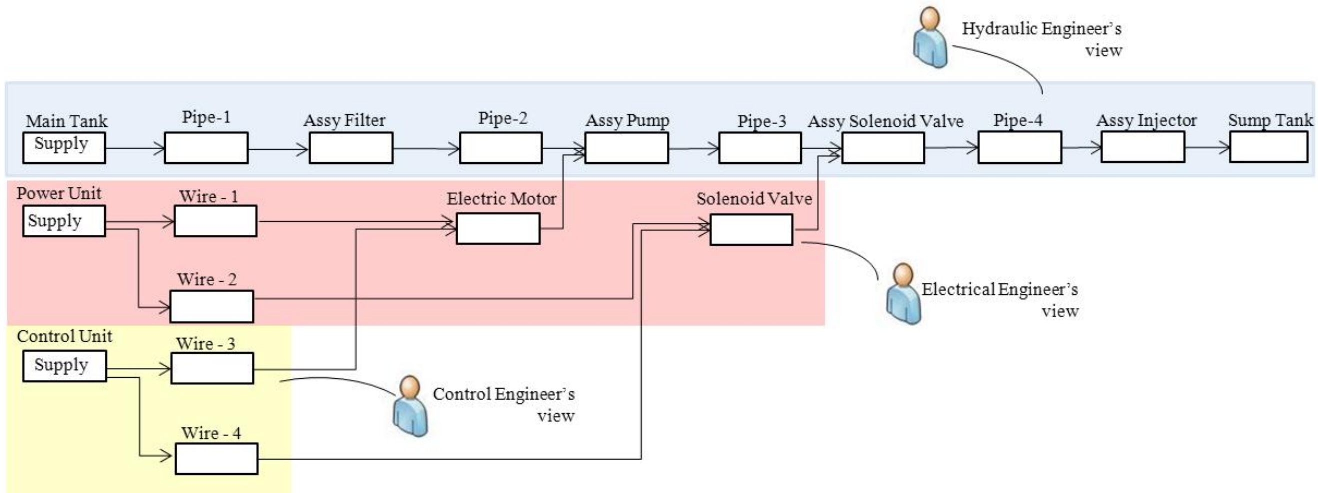


Figure 10. Multi-dimensional view of the fuel system.

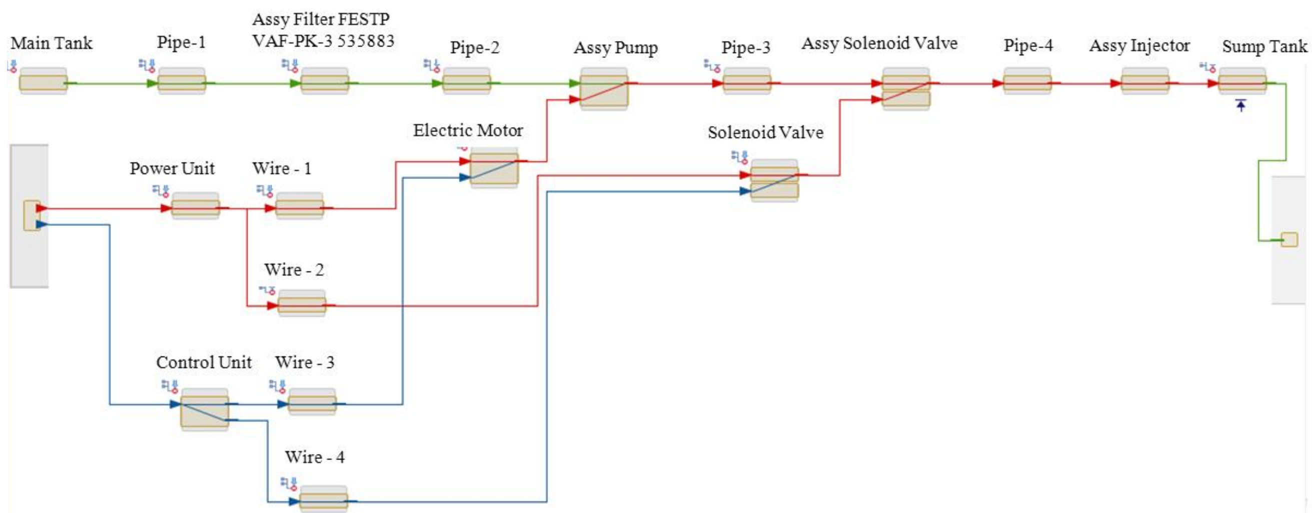


Figure 11. Fuel system MADe functional model.

5. SYSTEM DESIGN – BEHAVIOR AND RISK IDENTIFICATION MODEL

The components models in Figures 8 and 10 contain the function of each individual component, the input and output flow(s) and the causal relationship between them. The causal relationship maps out the physical behavior of a component. For a normally closed valve, the function is depicted in Figure 12. The functions of this component will be to channel the flow and also to regulate the amount of volumetric flow rate in the system. The bigger the pressure at the inlet of this valve, the larger amount of volumetric flow channel through the outlet as hydraulic energy. Increasing the linear velocity input flow will allow more volumetric flow rate through the outlet, therefore a positive causal relation between these two parameters. In the case of a normally open valve, by increasing the linear velocity input flow less flow will be allowed to pass through the valve. This is actually captured within the component functional model in Figure 13 as a negative causal relationship between these two particular flows. Similar functional models are used to automatically generate the hydraulic dimension of the fuel system (Figure 9) that was sequentially updated with the electrical and control dimension (Figure 11). Input and output flows were connected in order to allow flows to be exchanged between components. The model in Figure 10 represents the healthy state of the fuel system – as it captures the way this system was intended to operate.

The functional dimension of each component (created by linking a 3D CAD component to a functional model of the respective component from the MADe library) contains failure modes associated to various parts that are forming the respective component. The failure modes are described as failure diagrams and they can support safety and reliability analysis by injecting failure diagram in this model. Failure diagram can also support the identification of the most critical components that will have to be monitored in order to support health management function.

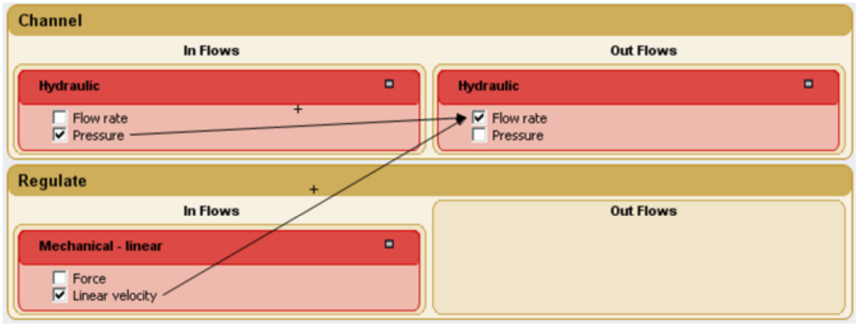


Figure 12. Functional model of a shut-off valve (normally closed).

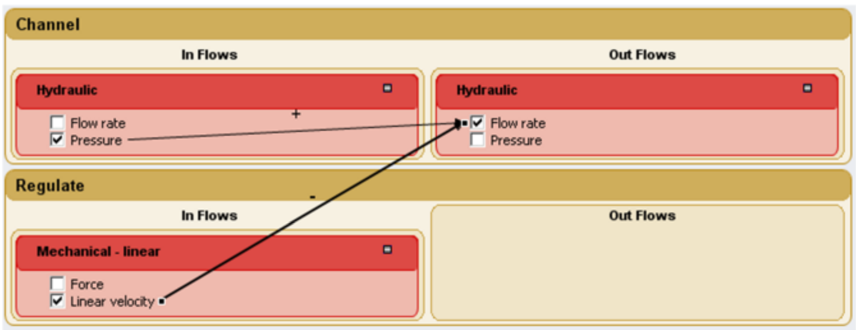


Figure 13. Functional model of a shut-off valve (normally open).

Failure diagrams are documented in MADe by using four different types of concepts (causes – mechanisms – faults - symptoms). They all get connected into a tree architecture and they will document automatically a model-based FMECA analysis. The advantages of a model-based FMECA versus traditional FMECA spreadsheets are highlighted by Stecki (2014). The failure diagrams can be as simple as the one depicted in Figure 14. Typically, this sort information is captured by the system integrators who are dealing most of the times at component level or line replaceable unit (LRU). Component manufacturers might want to define FMECAs at the part level and failure diagrams of a gear could shape as complex as the one depicted in Figure 14. The elements of the failure diagram are ultimately linked to the functional failure of a given component. This translates into a deviation from normality of one or several of the output functional flows of that component. For example: the function of the gear pump of this fuel system is *to supply volumetric flow* rate as *hydraulic energy* down the line. When this component is affected by one of the faults captured within the failure diagram from Figure 15, the volumetric flow rate generated by this pump will drop. This should be explicitly captured by the IVHM analyst as part of the functional model a pump (Figure 16). Engineering judgment should be encapsulated in the modelling activity when such models are created in the first place as part of a new MADe library. If available, this information will be retrieved as part of a functional model created following the automated process described in the previous sections.

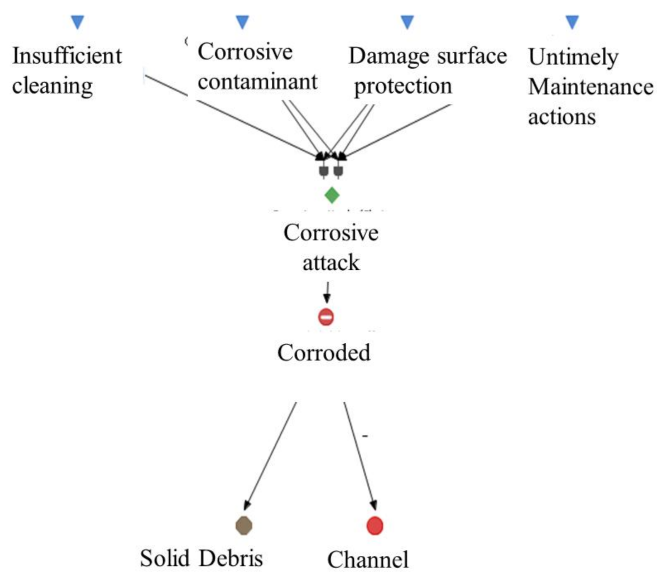


Figure 14. Failure diagram of a shut-off valve.

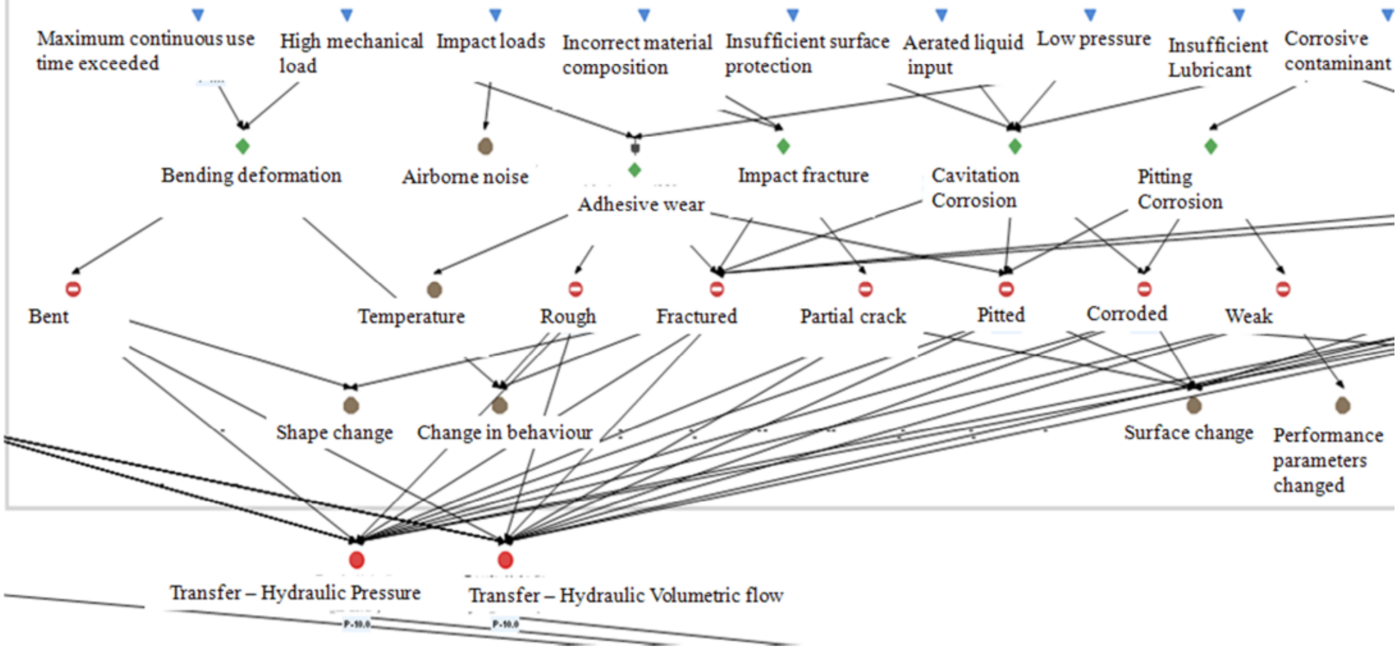


Figure 15. A fraction of gear pump failure diagram (failure diagram of the idle gear)

The correct selection of *High* or *Low* for the deviation of output flows for components affected by failure modes will enable the propagation of flows through the functional layer throughout the system (downstream). In order to capture the upstream propagation of faults within a complex system several enhancements have to be carried out on the functional model. For example, a clogged nozzle will automatically determine the output flow (*volumetric flow rate – as hydraulic energy*) to decrease, but there will also be some increase of the input flow to increase (*pressure – as hydraulic energy*). In order to describe this particular type of behavior feedback loops have to be manually added to the model (Figure 17). Assuming there are no leaks in this system, if less flow is coming out from the nozzle component, more flow will be pumped in the inlet pipe (Pipe-4 component) as input flow. The positive causal relationship between input and output flow of the pipe component determines the output flow to increase, which is an accurate representation of the behavior of this part of the fuel system when clogging phenomena is occurring. This representation was achieved using a negative feedback loop (*F-*). This approach was repeated throughout the entire system, for each individual component in order to fully capture the effects of faults on the overall system. This correlation has to be made by using expert knowledge or by using physics-based models that are capable of describing the behavior of the system under faulty scenarios.

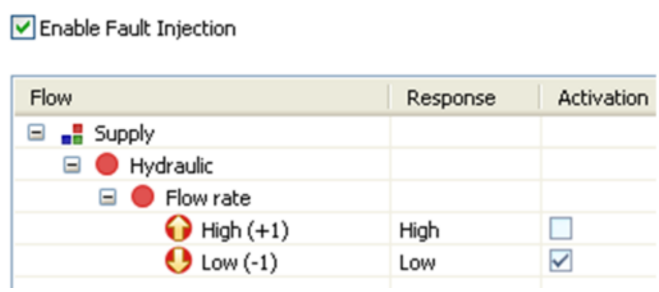


Figure 16. Engineering rational related to the effects of failure modes on the output functional flow of a component.

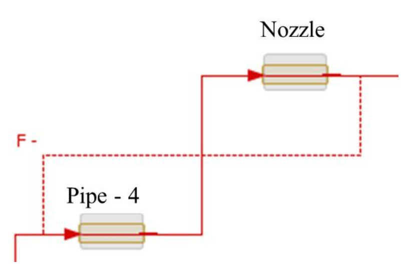


Figure 17. Functional feedback loops.

Complexity of the failure diagrams might not always be positively received by the IVHM analysts. A way to overcome this issue is to establish criticality figures for the elements of a failure diagram, calculate the risk priority numbers (RPN) of each individual components (RPN=Occurrence x Severity x Detectability) and tackle top x most critical components of the system in order to meet specific budget and time targets for the development of IVHM capability. This approach is not new, but the entire health management development process can be automated by using COTS software tools that allow execution of functional models automatically from the 3D representation of a complex asset.

This automated approach enables the identification of system-level risks and it can be applied for new or legacy systems. Selection of the test points (incl. the sensor identification and optimization analysis) for the fuel system is directly derived from the functional model developed in MADe. Sensor locations are highlighted in Figure 18.

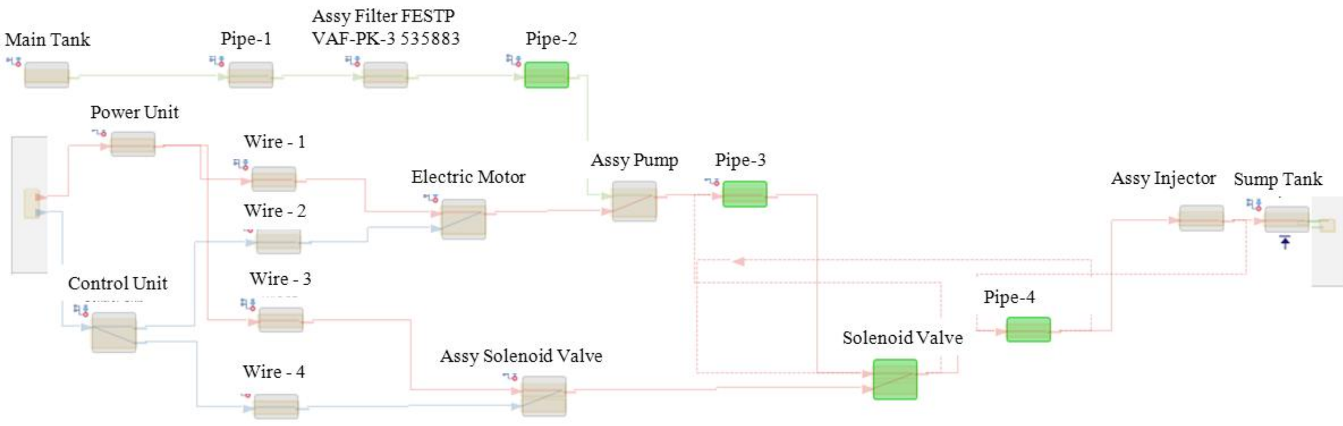


Figure 18. Test points selection fuel system

6. CONCLUDING REMARKS

The overall aim of this work is to enhance the health management development process and to support the execution of this process using COTS software tools. Since the CAD models tend to reside these days in the center of the overall engineering process, this paper describes step by step the workflow of creating functional models automatically from CAD models that were previously developed by the system designers. The functional models can be further enhanced by capturing failure diagrams to support safety, reliability and IVHM analysis. Using a laboratory fuel system design use-case, we demonstrated which steps are fully automated and which require manual manipulation in order to construct the functional model of the system being study. The functional model was previously constructed as part of a different project (by a different IVHM analyst) and the overall task took 3-6 months. Using the CAD import feature in MADe, the CAD model and a predefined Fuel System MADe functional library, the same system was functionally modelled in less than 1 month (this included the time to construct the CAD model of the fuel system at the part level). Once developed, the functional model captures system's behavior under healthy conditions. A fair amount of information has to be manually added to this functional model to reflect system behavior under faulty conditions and to ensure it captures the overall effects of the failure mode universe throughout the system. The effects of failure modes throughout the system (downstream and upstream) have to be mapped out manually within this process. In MADe, this was carried out using the feedback loop mechanism. The workflow presented in this paper supports the consistency through construction of models ultimately used for Asset Design and IVHM Design, and the existent health management development process was enhanced by adding a feature that allows passing the geometry between the Asset Design and IVHM Design in an automated manner. The automation in construction of context-sensitive functional models for complex systems forms part of the future work. This will be achieved by linking the functional layer to the physics-based models (that should encapsulate system's behavior for both healthy and faulty scenarios) of these systems.

ACKNOWLEDGEMENT

This research is funded by the IVHM Centre, Cranfield University. The authors would like to thank Cameron Weick and Jacek Stecki at PHM Technology for valuable discussion and guidance during this project.

REFERENCES

Canedo A., Schwarzenbach E, Faruque M.A.A. (2013). Context-sensitive Synthesis of Executable Functional

Models of Cyber-Physical Systems. *ACM/IEEE 4th Interrnational Conference on Cyber-Physical Systems* (ICCPS'13), pp. 99–108.

CATIA™, Dassault Systems, http://www.3ds.com/products-services/catia - Accessed 2014.

Hirtz, J., Stone, R.B., Szykman, S., McAdams, D.A. & Wood, K.L. (2002). A functional basis for engineering design: Reconciling and evolving previous efforts. *Technical report* NIST.

Komoto, H., & Tomiyama T. (2012). A framework for computer aided conceptual design and its application to system architecting of mechatronics *products*, *Computer Aided Design*, 44(10), pp. 931-946.

Kurtoglu, T., & Campbell, M.I. (2008). Automated synthesis of electromechanical design configurations from empirical analysis of function to form mapping. *Journal of Engineering Design*, 19.

MADe™, PHM Technology, http://www.phmtechnology.com – Accessed 2014.

Modelica Association, Modelica Standard Library, http://modelica.org/library/Modelica/.

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.

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.

Stecki, J., & Stecki, C. (2013). Computer Aided Design in Condition Based Maintenance, *Proceedings of The British Institute of Non-Destructive Testing (BINDT) Conference*, Kraków, Poland.

Stecki, J., Rudov-Clark, S., & Stecki, C. (2014). The Rise and Fall of CBM (Condition Based Maintenance). *Key Engineering Materials*, vol. 588, pp. 290-301.

Stone, R.B., & Wood, K.L. (2000). Development of a functional basis for design. *Journal of Mechanical Design*, 122(4), pp. 359-370.

Uckun, S. (2011). Meta ii: Formal co-verification of correctness of large-scale cyber-physical systems during design, *Technical report*, Palo Alto Research Centre.

BIOGRAPHIES

Octavian Niculita gained his BSc in Automation Control and Computer Science (Technical University of Iasi, Romania). He undertook his PhD research at TUIASI, Romania and at the University of Ferrara, Italy as part of the European Doctorate of Sound and Vibration Studies. Since 2009 he has been actively involved in several projects of the IVHM Centre regarding health management development process and construction of test facilities for assessment of IVHM design and deployment software tools for high-complex, high-value systems.

Professor **Ian K Jennions** career spans over 30 years, working mostly for a variety of gas turbine companies. He has a Mechanical Engineering degree and a PhD in CFD both from Imperial College, London. He has worked for Rolls-Royce (twice), General Electric and Alstom in a number of technical roles, gaining experience in aerodynamics, heat transfer, fluid systems, mechanical design, combustion, services and IVHM. He moved to Cranfield in July 2008 as Professor and Director of the newly formed IVHM Centre. He has led the development and growth of the Centre, in research and education, over the last five years. Ian is on the editorial Board for the International Journal of Condition Monitoring, a Director of the PHM Society, contributing member of the SAE IVHM Steering Group and HM-1 IVHM committee, a Fellow of IMechE, RAeS and ASME. He is the editor of three recent SAE books on IVHM.

Miguel Medina holds a BSc in Industrial and Systems Engineering (Monterrey Institute of Technology, Mexico) and a minor degree in Aeronautics and Energy (National Institute of Applied Sciences of Lyon, France). He gained his MSc (Hons) in Global Product Development and Management at Cranfield University. Since 2008 he has been involved in Manufacturing and Product Development in the Aerospace sector. Currently he is working as a Senior Continuous Improvement Leader in AeroMexico-Delta TechOps, a world class provider of aviation MRO services.