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Design and development of a testbed capable of supporting technical diagnostics of complex systems

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Abstract. Providing high quality data for the test and evaluation of diagnostic algorithms is of high importance for modern complex systems. To this end a testbed capable of supporting degradation of components and instrumentation has been designed, manufactured and commissioned. It has specifically been designed to replicate five component and instrumentation faults with high accuracy and repeatability for different degrees of severity. This paper documents the design process and shows some of the capabilities of this platform.

1. Introduction

Optimized and reliable diagnostic solutions contribute to increased availability and reduced maintenance costs for high-tech high-value systems. As a result, the software market provides a significant number of diagnostic software packages for design and implementation of such solutions. Assessment and evaluation of such software can be a lengthy and painstaking project on real machines due to the large number of uncontrollable parameters that affect the acquired data. An alternative approach, adopted here, is to develop a demonstrator platform in which known faults can be introduced, accurately and repeatable, and their consequences monitored. In this work, a testbed capable of producing high quality data representing normal and abnormal scenarios has been built. The data can be incorporated into a consistent framework for evaluating the diagnostic design analysis, diagnostic reasoning and prognostic software packages.

2. Scope and description of the testbed

The laboratory test-bed represents a UAV fuel system and its associated electrical power supply, control system and sensing capabilities. A wide range of fault types can be injected into the rig so that it can produce benchmark datasets to evaluate and assess diagnostic tools. Single and multiple-fault scenarios can be introduced together with incipient and abrupt types of faults. Running representative tests on a system is always problematic, because of the time, cost and reproduction constraints involved in capturing any significant degradation. To create any significant degradation requires running tests over significant periods of time. Additionally, this cannot be reproduced easily, and is costly. Three different approaches to a solution could be taken. First, accelerated testing; this can be achieved by increasing the duty of the components or by manufacturing them out of less durable

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materials. Second, by accurately knowing the degradation modes to be investigated, the components could be machined to represent the degraded mode – often referred to as 'seeded fault' testing. This only represents one snapshot in the wear process but could be repeated gradually increasing the effect. Simulation may be necessary to aid this process. Third, by emulating some degradation modes, e.g. a filter replaced by a direct-proportional valve, so that a clogged filter failure mode could be simulated by gradually closing the valve, in controlled manner. It is the latter of these three approaches that is adopted here. The findings of the 2000 Aircraft Fuel System Safety Program Report prepared by the International Aviation Industry through the design/manufacturing reviews and fleet-sampling inspections show that fuel tanks and fuel systems very rarely exhibit faults, and that manufacturers' design requirements are conservative and provide ample design margin as well as built-in redundancy. However, when integrated on a platform, the failure of a component in such sub-systems can have a major impact on other systems. The effects of these types of accidents very often propagate at the fleet level when such situations occur. In this paper, a series of five different faults representative of the major causes of disruption to modern fuel delivery systems have been simulated on the fuel system testbed. These are: a clogged filter, a malfunction of the gear pump, a shut-off valve stuck in an interim position, a leaking pipe and a clogged nozzle. Each failure mode has been simulated under different degrees of severity. Additionally, three different types of failure/malfunction of instrumentation were considered to investigate the effects on the accuracy of the diagnostic solution. The paper describes three aspects of the fuel system test rig: i) the scope and the description of the fuel system rig ii) system design, verification and validation iii) the results of the initial set of tests covering healthy and faulty scenarios for hardware and instrumentation. Repository data sets for diagnostic and prognostic assessment are publicly available [1], [2]. NASA's ADAPT is a test-bed specially designed to enable the assessment of the effectiveness of various diagnostic techniques. The realistic datasets produced by the NASA ADAPT test-bed were used to evaluate various diagnostic tools in an integrated framework. The Diagnostic Competition defined by NASA Ames Research Center is a good example of how to find the best diagnostic solution for a given problem against a well-defined set of performance and effectiveness metrics. The main drawback of repository data sets is the fact that they were created for assessment of algorithms/software tools used for implementation of the operational part of the health management. Since most of the research undertaken focuses on real-time diagnostics and prognostics development, the design stage for properly setting the scene for the design and development of instrumentation is still missing [3]. Many different software tools like eXpress™, TEAMS™, ADVISE, Design PHM™ have been designed to aid the development of PHM solutions in maximising the efficiency of the feature detectors, minimising diagnostic ambiguity and optimising diagnostic tests for sensitivity and accuracy. Existing tools use different approaches to represent the system and to diagnose faults and have a wide range of capabilities. There is still the need to develop reliable benchmarks to quantitatively assess performance and effectiveness of the testability strategies identified by such type of tools. The proposed fuel system testbed is shown in Figure 1. Having a size similar to a UAV fuel system allows the rig to be bench-top scale, minimising cost and maximising ease of operation. The testbed consists of the following components: main and sump tanks, external gear pump, polyurethane tubing, solenoid shut off valve, direct proportional valves, control modules for pump, direct proportional valves and shut-off valve, instrumentation (absolute and gauge pressure sensors, flow meters and one contrast sensor to measure pump speed) for control and data acquisition purposes. In this paper, only the feeding engine operating mode was analysed, but the rig is capable of simulating re-circulation (by guiding the fuel back into the main tank) in order to emulate centre of gravity control conditions. Five different failure modes were accommodated by the system (FM1 - failure mode of a clogged filter, FM2 – failure mode of a degraded pump, FM3 – Failure mode of a stuck valve, FM4 – failure mode of a leaking pipe, FM5 – failure mode of a clogged injector). These five faulty scenarios of the hardware components were complemented by malfunction of instrumentation meant to detect and isolate the faults to make the test bed as representative as possible for a real system.

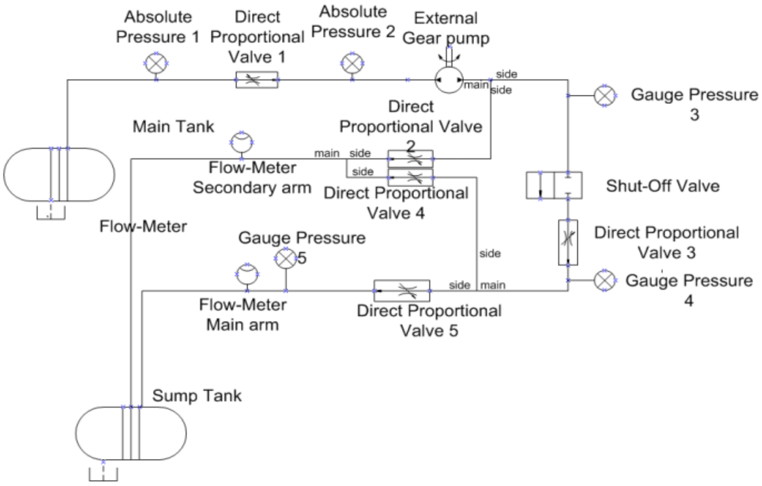

Figure 1. Fuel system schematic highlighting the fault emulation implementation

3. Initial results characterizing the failure of hardware components

Five different types of faults were considered as part of this test bed and each of them was emulated using the opening/closing of a specific direct-acting proportional valve (clogged filter – DPV1, degraded external gear pump – DPV2, shut-off valve stuck in a mid-range position – DPV3, leaking pipe – DPV4, clogged nozzle – DPV5). Some of the DPVs replaced the actual components under the faulty regime (e.g. DPV1 replaced the filter element) and some were added to emulate a faulty scenario (by gradually opening the DPV4 – a scenario of a leak with different degrees of severity can be emulated in very controlled manner).

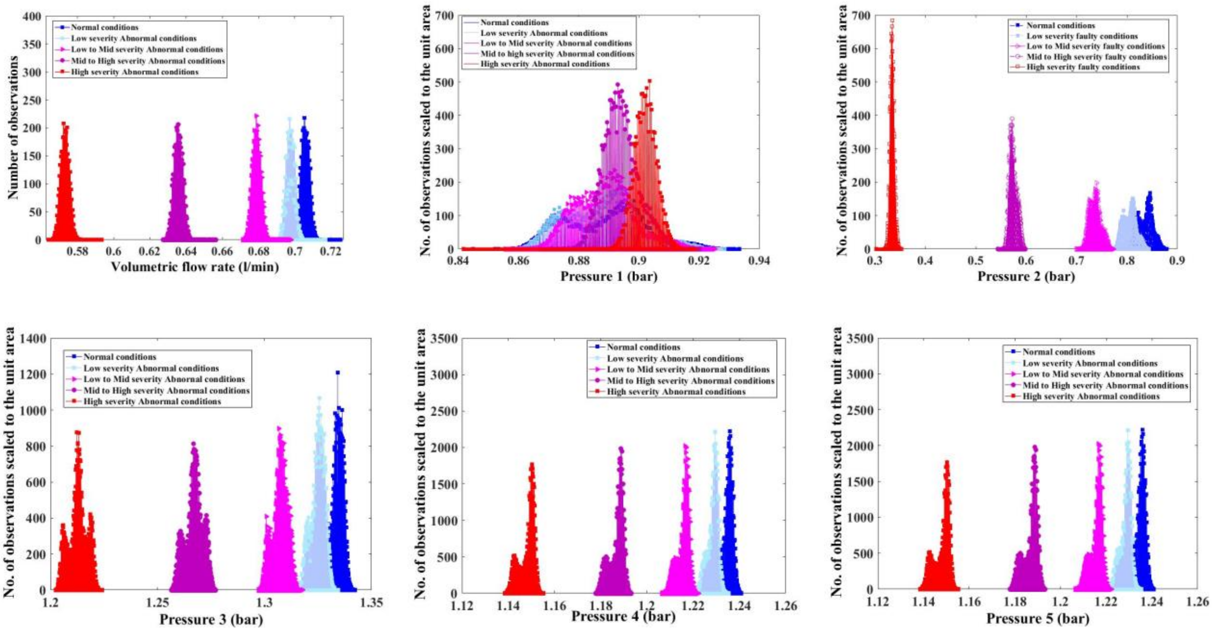

Figure 2. Characterisation of the effects of a clogged filter under various levels of severity

Pressure reading at locations 2, 3, and 4 were identified using a physical-functional approach as offering the maximum fault detection and fault isolation coverage (100%) within the fault universe considered for the analysis [4]. At the very same time, malfunction of the instrumentation was also considered for the analysis and the effects of forcing to zero a pressure reading (SF1), by physically disconnecting the power supply for these pressure sensors (SF2) or the presence of an offset by multiplying the output with a factor between 1 and 2(SF3) has some serious consequences on the accuracy of the fault diagnostic. Figure 3 captures the misdiagnosis when any of the malfunctions of the instrumentation was present in addition to the presence of a faulty hardware component (FM1 – FM5). Any red block outside the correct diagnostic output (represented by the column highlighted in the red dashed line) is a false alarm (false positive or false negative).

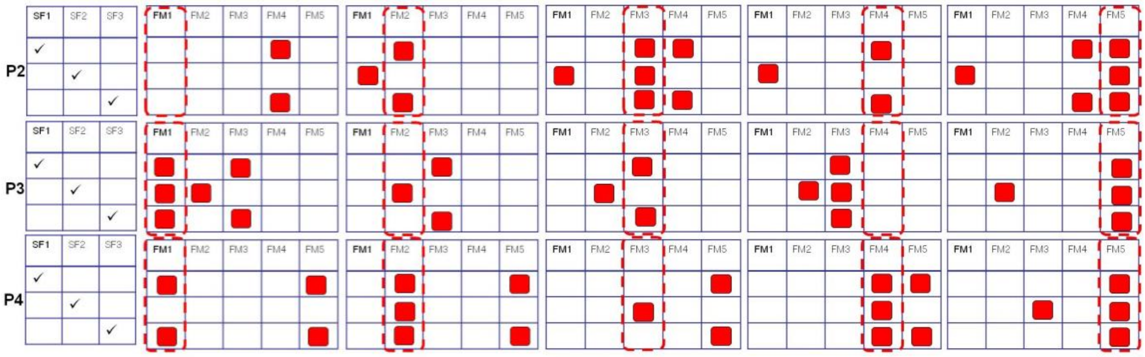

Figure 3. Effects of instrumentation's failure on the output of the diagnostic engine

4. Concluding remarks

This paper described a testbed which has been constructed to produce a reference data set to be used for assessment and benchmarking of various diagnostic software tools and techniques. The fuel rig has been designed, commissioned and a verification and validation process carried out to fully understand and document its behavior. Tests considered both component and system level approach and the fault injection mechanisms targeted both hardware components and instrumentation. Measurements were treated under this verification and validation process from the repeatability, stability and uncertainty point of view. It was found that there is an operational envelope within which system pressure and volumetric flow rates can be accurately specified and measured under steady and transient conditions.
Five representative types of faults have been physically simulated and their effects on pressure and flow rates at defined locations at a range of fault severities have been monitored. The extent of pressure and flow rate change is a function of degree of severity of the fault. In addition, 15 different scenarios characterizing abnormal behavior of the instrumentation were investigated and an initial snapshot of their effects on the accuracy of the diagnostic engine was presented.

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