MODEL-BASED DIAGNOSIS STUDIES OF COMPLEX FLUID MECHANICAL AIRCRAFT SYSTEMS

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Abstract

This paper presents a long term project within diagnosis of fluid mechanical aircraft systems carried out at Saab Aerosystems in cooperation with Luleå University of Technology. Saab Aerosystems has been working with new techniques for diagnosis systems while the research at Luleå University of Technology has been on requirements management for diagnosis system.

The focus is on maintenance and not on system safety due to the well working methods used within system safety.

The paper gives a brief introduction to model-based diagnosis and an overview of the performed studies within model-based diagnosis for complex fluid mechanical systems. It also gives an introduction to requirements identification for diagnosis systems.

1. Introduction

No fault found (NFF) is a serious problem that increases life support cost (LSC) and reduce availability. For complex systems such as the systems in the multi-role combat aircraft Gripen, aircraft monitoring and diagnosis are essential to gain airworthiness and safety. Unfortunately for aviation in general, a great amount of the line replacement units (LRU) removed from the aircraft are classified as NFF, when neither the aircraft diagnosis system nor the technician have properly isolated a faulty component or the alarm as false.

In a long-term project, founded by Saab Aerosystems and the National Aeronautics Research Program (NFFP), requirements management and new techniques for diagnosis of complex fluid mechanical aircraft systems are studied. Example of such systems are fuel systems and environmental control systems (ECS), see a schematic view of the Gripen fuel system in Fig. 1. These systems consist of both mechanical equipment, electrical equipment and control units. The complexity of such systems is high due to the high integration with other systems and the excessive control logics in electronic control units.

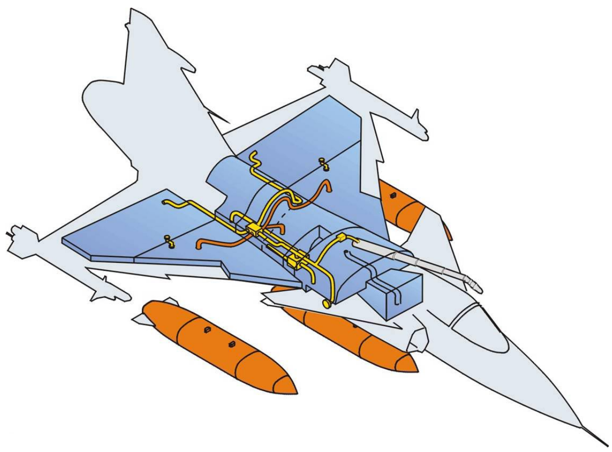

Fig. 1 The Gripen fuel system.

Without diagnosis systems, only staff with long experience may isolate faulty components in such systems. Robust equipment and properly functioning fault detection and isolation system are therefore essential for airworthiness, safety, availability and maintenance - especially for UAVs and civil aircraft.

Diagnosis systems technology is a fairly new research area that has gained increased importance at universities during the last 20 years. One of the more interesting new techniques is model-based diagnosis. Today, such diagnosis is realized in many applications.

The following two tasks have been in focus for the project:

- Requirements management for complex systems: Which faults should be monitored by a diagnosis system and which should not? Why should they be monitored? Who is the stakeholder?
- Development of diagnosis systems: How can the process to develop model-based diagnosis for complex systems be simplified? How can concepts be designed and verified?

The research at Luleå University of Technology has been concentrated on the first task while the work at Saab Aerosystems has been within diagnosis systems development. The work has been carried out in cooperation with the customer support and system development departments at Saab Aerosystems. It has been supported by seven Master's theses from Linköpings universitet where five will be mentioned here.

2. Background

The multi-role combat aircraft Gripen is the first fourth generation combat aircraft in service, which it has been since 1997. The system layout of Gripen is shown in Fig. 2.

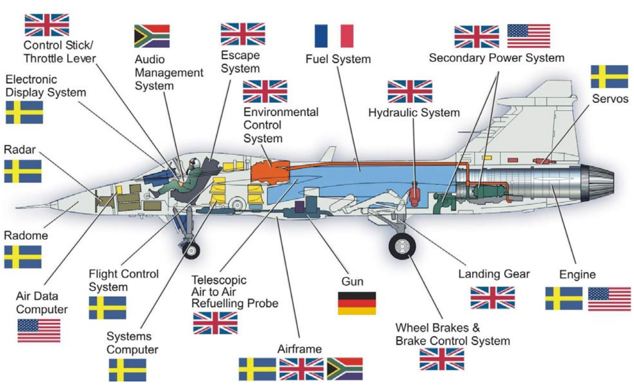

Fig. 2 The system layout in Gripen

Studies of a new combat aircraft system begun in the 1970s and the contract was sign in 1982 between the Swedish Defence Material Administration (FMV) and Industry Group (IG JAS). It was early stated in the project that the Gripen should not only be a high performance aircraft it should also be cost effective, see [1]. The requirement was to break the increasing Life Cycle Cost (LCC) at the same time as increasing the availability and the combat performance.

The digital infrastructure and highly integrated computer systems permit a flexible environment for adaptation of new technology and implementation of new functionality. This together with the sensors in the systems is the foundation for an efficient diagnosis system and enables the implementation of model-based diagnosis. An overview of the different tests used is shown in Fig. 3. The different tests are functional monitoring (FM), redundancy management (RM) and built-in test (BIT), where BIT is devided into safety check (SC), functional check (FC) and fault isolation (FI).

What	**FM/RM**	**BIT**		
		SC	**FC**	**FI**
When	During normal operation conditions	When system is powered up	After maintenance	After FM/RM, SC or FC has detected a fault
Why	Detect h/w fault or abnormal behavior. Warn pilot or change operating mode	Detect fault to achieve safety requirements	To verify functionality after LRU change	Localize faulty LRU after detection

Fig. 3 Aircraft level tests in Gripen.

The prognostics and health management (PHM) functionality in the Gripen system is continuously further developed, see [2]. This paper describes how the workflow to define pilot warnings, recording needs, fault isolations are integrated to reduce development time and reuse data. The functionality in the aircraft and the Maintenance Ground Support System (MGSS) are also described.

3. Model-based diagnosis

In model-based diagnosis, a model is used to estimate output signals $y(t)$ of a system based on the input signals *u(t)*, see Fig. 4. The basic idea is to compare the estimated signals with sensor data in the real system and by that identify discrepancies that may be caused by faults in the system. For a detailed description of model-based diagnosis see for example [3].

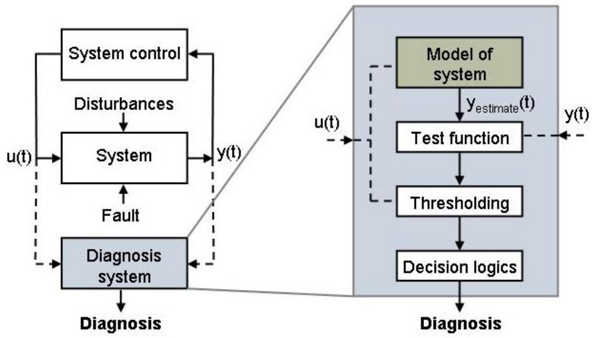

Fig. 4 Model-based diagnosis.

Model-based diagnosis can be divided into four parts; model of system, test quantity, thresholding and decision logic.

3.1. Model of system

Diagnosis of system has traditionally been performed with limit checking, which means that an alarm is set when a sensor signal leaves its normal level. This can be considered as a very simple model that in many cases are sufficient. But when the systems performance largely depends on the operating condition, for example in fighter aircraft, this might be a to coarse method. Selecting the limit for alarm might be very difficult if the diagnosis system should be useful in for example the whole flight envelope. The limit should be selected to avoid false alarms, but should of course be narrow enough to detect faults in the system. Different limits can be used at different operating conditions to solve this problem, which essential is a model.

Why not use a model that can estimate a sensor signal based on other sensors? This would make it possible to estimate a normal level for the sensor signal in any operating condition and the probability for false alarms as well as missed faults can be decreased. Within this project the focus has been on physical models and to some extent on black-box models based on system identification. There is of course other alternatives such as statistical based models, discrete models, AI-based models, etc. In any case a simple model as possible that fulfills the requirements should be chosen. In some cases a simple limit is sufficient and in some a complex physical model is needed.

It is although always important to know for which operating conditions the model is valid. The requirements on the model is also largely varying with the intended use, on-board real-time systems requires one type of models while off-line system for fault localization implies other requirements on the model.

3.2. Test quantity

A test quantity is used to compare each signal's estimate with its measurement. The test quantity should be small in the fault free case and significantly deviate from zero when a fault is present. A straightforward way, that also is most commonly used, is to form a residual by comparing a sensor signal with its model estimate, also called a consistency relation. The test quantity $T_k(t)$ for test k is defined as:

$$T_k(t) = y_k(t) - \hat{y}_k(t) \qquad (1)$$

where $y_k(t)$ and $\hat{y}_k(t)$ is the sensor signal and the estimate by the model, respectively. A test quantity can also be formed by defining a residual between two estimates of the same signal based on different sensors.

3.3. Thresholding

A test quantity will usually deviate from zero even in the fault free case, due to disturbances, measurement accuracy and model errors. It is therefore necessary to define a threshold for setting an alarm. This can for example be done by a constant limit for the test quantity. This will although require a high model accuracy to avoid false alarms or missed faults at dynamic conditions. To solve this for dynamic conditions an ordinary filtering of the output signals or adaptive thresholds can be implemented.

Adaptive thresholds can be defined as:

$$J_{adp}(t) = kH_{LP}(s)(|H_D(s)u(t)| + c) \qquad (2)$$

where $H_{LP}(s)$ and $H_D(s)$ are filters and k and c are constants. The filter $H_D(s)$ is a weight in the frequency domain that makes the threshold larger for frequencies where the model accuracy is low and vice versa, normally $H_D(s)$ is a high pass filter. For smoothing the threshold the low pass filter $H_{LP}(s)$ is used. The constant c is used to get a threshold also at steady state conditions and the constant k is used to scale the threshold.

3.4. Decision logic

By using so-called decision logic based on the test quantities and the faults that are monitored, the fault can be isolated either to a faulty component or a group of components that contains the faulty component.

This is done by using the test quantities to decouple faults in the system. A fault is decoupled when it does not affect the test quantity. A set of test quantities are used in hypothesis tests to identify which faults that are present in the system. The hypothesis test has two regions; the null hypothesis H_k^0 and the alternative hypothesis H_k^1. The null hypothesis holds if the present fault mode belongs to a set M_k of fault modes and the alternative hypothesis holds if the present fault mode not belongs to M_k. In the latter case does the present fault mode belong to the complement of M_k, i.e. M_k^c. This is formally written as:

$H_k^0 : F_P \in M_k$ "The faults in M_k can explain data"

$H_k^1 : F_P \in M_k^c$ "No fault in M_k can explain data"

where F_p denotes fault mode p. The defined hypothesis tests δ_k leads to a diagnosis S_k, which are combined to generate the final diagnosis S as:

$$S = \bigcap_k S_k \qquad (3)$$

This can be illustrated in a so called decision structure, see Fig. 5. The entry s_{kj}, on row k in column j in the decision structure are; 0 if test δ_k not is affected by the fault in column j (decoupled), 1 if test δ_k is affected by the fault in column j and X if test δ_k may be affected by the fault in column j.

	NF	F1	F2	F3
δ_1	0	0	X	0
δ_2	0	0	X	1
δ_3	0	X	0	X

Fig. 5 Example of a decision structure.

For the example in Fig. 5 test δ_2 will respond to fault F_3 and test δ_3 may respond. If δ_1 and δ_2 respond the partial diagnoses $S_1 = \{F_2\}$ and $S_2 = \{F_2, F_3\}$ are given, which are combined to the diagnosis:

$$S = S_1 \cap S_2 = \{F_2\} \cap \{F_2, F_3\} = F_2$$

In this case the present fault could be isolated to F_2. In other cases the fault may not be isolated, but still detected. This means that tests will react to the fault but it is not possible to isolate a single fault.

The output from the decision logic is the diagnosis S, which is a single fault corresponding to a fault in a single LRU or a number of possible faults corresponding to a number of possible faulty LRUs.

4. Requirement identification

Complex systems may never be fully monitored for practical and economic reasons. Without early planning of the diagnosis system, practical problems may arise and development time increase. The studies showed the importance to choose early during development which faults that should be monitored and, consequently, which sensors and test quantities that should be used by the diagnosis system.

A key feature for a successful diagnosis system is the selection of which sensors that shall be implemented in the system. Traditionally, first the sensors necessary for the control logic is introduced and then the sensors needed to fulfill system safety requirements are selected. The diagnosis functionality is then limited by these sensors and from a maintenance point of view the implemented sensors may not be the optimal selection to meet the requirements on for example LSC and availability. Some additional sensors may be needed for efficient maintenance. To success in this work it is essential to early in the system development process identify all stakeholders and their requirements on the diagnosis system.

The research at Luleå University of Technology has therefore been focused on both diagnosis systems stakeholders and their requirements, see [4]. A method has been suggested with the aim to systematically identify the faults which should be monitored. The foundation in the method is the stakeholder system and the technical system. The first part is to identify the stakeholders and to correlate them with the requirements in a stakeholder requirements matrix. This indicates which stakeholders that have interests in information from the diagnosis system. Examples of different stakeholders are:

- Pilot
- Technician
- Planners: mission and maintenance
- Developers
- Flight safety investigators
- Customer

All stakeholders want information from the diagnosis system, but with different information. For example, the pilot wants to know if there are any failure present and what action that should be taken. The technician's focus is on fault localization and maintenance data. He wants to know which LRU that should be replaced, i.e. exact fault localization. The developers want data for further improvements of the system's design.

In parallel, the technical system should be analyzed to identify the components in the technical system and its functions, and correlate them in a system function matrix. This might seem to be a simple task, but for complex and highly integrated system it is an excessive work. The purpose is to identify which system parts that are used to fulfill a specific function, which is important information for identification of possible causes to loss of a specific function.

In the next part the stakeholder's requirements and the system functions are correlated in a joint system. This serves as input to the final part, which is an enhanced Failure Mode and Effects Analysis (FMEA). The FMEA is modified to also estimate the influence of each failure mode's influence on the system's LCC. Four measurements for evaluation of the system and its diagnosis system are proposed:

- Immediate loss
- Corrective cost.
- Cost for loss of function
- Time for corrective actions and non-availability

This makes it possible to evaluate if the system and its diagnosis system meet the requirements on for example non-availability. If not, actions must be taken, for example improve the fault localization, redesign the system to shorten the time for corrective actions, etc.

The proposed method was evaluated by applying it on the Air-to-Air refueling functionality of Gripen, see [5]. The method was proven to be successful and to a large extend also useful at the system design work. Possible improvements of the method were proposed and implemented. For example was it proposed to use a scoring method in the concept development phase and perform a more detailed analysis in the detail design phase. An example of the FMEA is shown in Fig. 6 for one failure mode.

No.	Designation	Example
0	Definition of the system	Fill tanks full during flight
	Function number	1.1
1	Function / requirement	Pilot selects extend on the AAR control switch
2a	Functional failure (loss of function) / unfulfilled requirement (fault)	Signal is not recorded by GECU
2b	Failure / fault mode	Control switch broken or Communication line to GECU broken or GECU does not register in signal
3	Failure effect	
3a	Effect on analyzed system	GECU gets no signal to go into AAR mode
3b	Effect on neighboring system	GECU can not signal to open AAR door
3c	Effect on superior system	Not possible to carry out AAR
4	Foundation for prioritization FM/RM	
4a	The frequency of the failure mode (component)	10^{-7} 10^{-6} 10^{-8}
4b	The frequency of the failure mode (function)	$1,11*10^{-5}$
4c1	Safety hazard category	3
4c2	Performance hazard category	3
4d1	System safety implications	12
4d2	System performance implications	12
5	Present diagnosis system	
5a	Detection of failure	Assumed to be 100 % accurate
5b	Failure / fault localization	None
6	Foundation for prioritization BIT	
6a	Cost of maintenance	3 2 1
6b	LCC affect when component fail	6 6 1
6c	Time for corrective actions	4 3 2
6d	Availability affect when component fail	8 9 2

Fig. 6 Example of the enhanced FMEA, from [5].

5. Model-based Diagnosis Studies

In the following sections a number of studies carried out within the project are briefly presented.

5.5. Model-based diagnosis of the ECS

Fault detection and isolation with model-based diagnosis have been demonstrated for the distribution sub-system of the ECS in this study, see [6]. A schematic view of the distribution system is shown in Fig. 7. The system consists

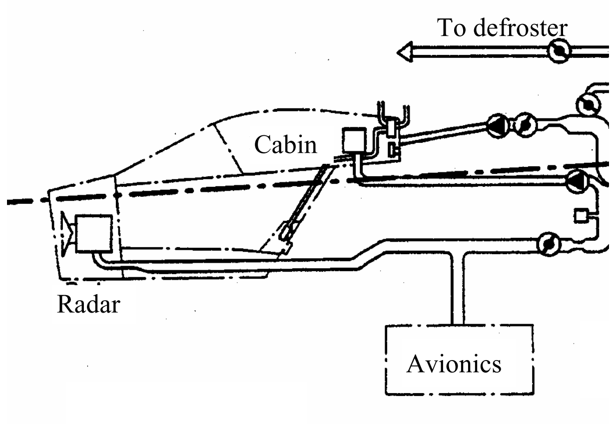

Fig. 7 Schematic view of the distribution sub-system in the ECS in Gripen.

of six valves that control the pressure, flow and temperature levels to avionics, cabin avionics, radar, defroster and cabin.

A concept of a model-based diagnosis system was designed in MATLAB/Simulink. The common problem with false alarms due to transients was solved by adaptive thresholds. A high pass filter of the input signal that causes the transients is added to the ordinary threshold then. The thresholds are increased during dynamic conditions and reduced during steady-state conditions. An example with a jamming valve is shown in Fig. 8 together with the estimate valve angle and its adaptive thresholds.

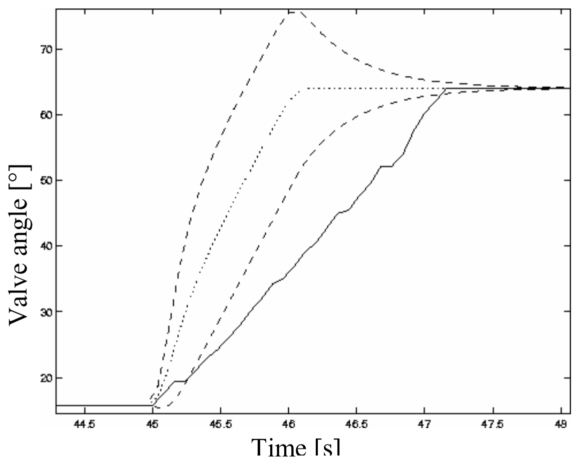

Fig. 8 A jamming valve. Measured angle (solid), estimated angle (dotted) and its adaptive thresholds (dashed).

This study showed that, even without adding any new sensors, 50% of the faults that had occurred in the distribution system could be properly isolated. The other faults could be detected and isolated to a group with two components.

5.6. Passive and active diagnosis

In this study active diagnosis was investigated to demonstrate the increase in diagnosis efficiency compared to only using passive diagnosis, see [8]. In the latter case is the system passively studied without affecting its operation, but with active diagnosis the system is actively manipulated to reveal faults. Mathematically does this means that more test quantities can be generated and thereby increase the fault isolation. Of course is it not possible to use active diagnosis due to safety reasons in some applications or during certain operation conditions. Active diagnosis is typical used at the safety check, but could most likely be more widely used.

In this study, active diagnosis was conceptual demonstrated for the tank ventilation and pressurization system in the fuel system in Gripen, see Fig. 9. The system is used to keep the tank pressure within allowable limits, for differential pressure transfer, prevent fuel boiling at high altitude and limiting the pressure at refueling overshoot.

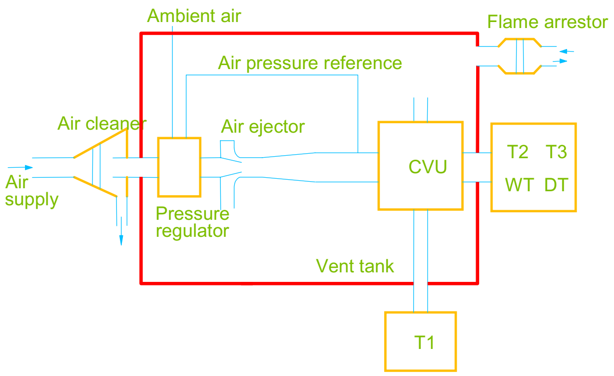

Fig. 9 Schematic view of the tank ventilation and pressurization system in Gripen.

A total of 14 fault modes was analyzed, faults in valves, sensors and leakages. The number of test quantities could be increased from 7 with passive diagnosis to 11 with active diagnosis. Which led to improved fault isolation, from 6 isolatable faults with passive diagnosis to 9 isolatable faults with active diagnosis. All faults were detectable with active diagnosis, which not was the case with passive diagnosis.

This study showed the potential with active diagnosis for applications where it is possible with respect to system safety.

5.7. Real-time models based on system identification

To develop real-time models for model-based diagnosis of a complex system is a time-consuming task. Therefore, the possibility to use system identification was investigated in order to speed up the work. For this study the tank ventilation and pressurization system used in previous section was used and the identified system is shown in Fig. 10. The pressure regulator was modeled separately in this case. The system identified, the G-system, has 6 input signals and 2 output signals in other words a MIMO-system. The output signals are simply the signals needed in the decision logic in the diagnosis system and the input signals are those affecting the output signals.

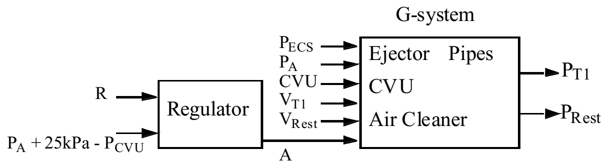

Fig. 10 The G-system that is modeled by system identification.

For the identification process a suitable set of data is needed, which must cover all operation conditions that the model will be used for. It was not possible to perform tests in aircraft so instead a detailed model in EASY5 of the fuel system was used to generate data. Example of the identified model implemented in the diagnosis system is shown in Fig. 11 with an incipient fault in a pressure sensor after 50 sec.

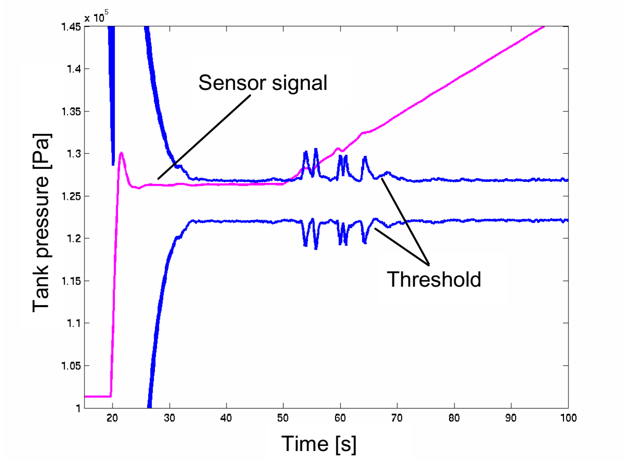

Fig. 11 Example with an incipient fault in a pressure sensor after 50 s.

The model is within the earlier defined thresholds but that there is a stationary offset at no fault. This is due to the fact that the identified model is a linear model that is used for non-linear system. The identified model together with the previously designed decision logic resulted in a correct diagnosis for all studied faults. The model was most likely fast enough to be used in a real-time system and significantly faster than the EASY5-model. The key issue is although that suitable data is available for the system identification process.

5.8. Utilizing Structural Methods

To success in development of a diagnosis system it should be developed highly integrated with the system development to get the necessary sensors into the system, see Fig. 12. A so called structural method was used in this study on a conceptual level to identify which sensors and test quantities that should be used for fault detection and isolation, see [9]. Structural methods make it possible, at a preliminary design phase, to perform an analysis of the expected fault isolability for a selected sensors configuration. For a thorough presentation of structural methods see [10].

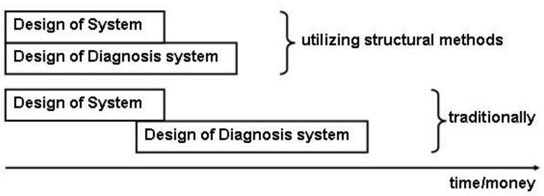

Fig. 12 Structural methods are used for conceptual design.

To perform an analysis of fault isolability with a structural method only a system concept is needed. In this study only a preliminary system layout of the fuel system for a UAV was used as input, see Fig. 13. The structural model was defined, which essential describes "connections" in the system, sensor configuration and possible faults.

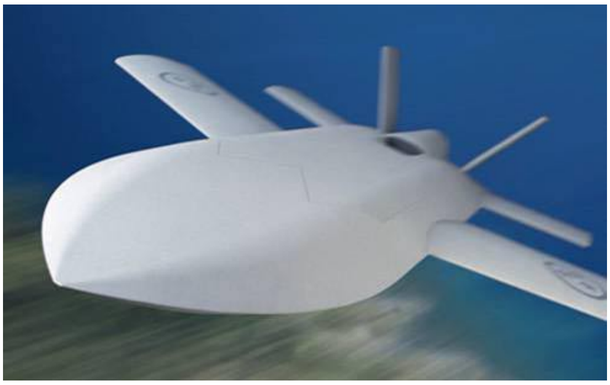

Fig. 13 A UAV concept.

The sensors are classified as required or optional and the fault modes are classified as necessary to isolate (F_I), detect (F_D) or not prioritized (F_N). For each sensor configuration the outcome of the analysis is a isolability matrix, one example is shown in Fig. 14. Only one "X" in the diagonal means that the fault can be isolated from all other faults, more than one "X" on arrow means that the fault only can be detected.

			F_I			F_D			F_N		
		NF	f_{I1}	f_{I2}	f_{I3}	f_{D1}	f_{D2}	f_{D3}	f_{N1}	f_{N2}	f_{N3}
F_I	f_{I1}		X								
	f_{I2}			X							
	f_{I3}				X						
F_D	f_{D1}					X					
	f_{D2}					X	X				
	f_{D3}						X	X			
F_N	f_{N1}	X	X	X	X	X	X	X	X	X	X
	f_{N2}									X	
	f_{N3}	X	X	X	X	X	X	X	X	X	X

Fig. 14 Example of an isolability matrix with fault classification.

The structural method was also combined with optimization for minimizing the number of sensors needed to meet the requirements on the diagnosis system. This can be done in different ways depending on which objective function that is selected, for example can the method be used to minimize a specific type of sensor or the total cost for the sensors.

This study showed that structural methods are a powerful tool in the development of a diagnosis system. It makes it possible on a conceptual level predict if the diagnosis system will meet the requirements on fault detection and isolation.

6. Lessons Learned

A number of findings have been made during the project such as:

- To success in development of a diagnosis system it is essential to early during the design of the supervised system also identify the requirements on the diagnosis system. This is necessary to ensure that the required sensors for the diagnosis system are integrated in the system.
- The systems in a modern fighter aircraft are highly integrated and complex, it is therefore important to pay extra concern to the interfaces between different systems (material groups).
- Many different rolls are involved in development of a diagnosis system, which to some extent makes it to be an organizational problem.
- The development of diagnosis system shall be highly integrated with the system development process.

7. Conclusions

The studies show a large potential to increase the outcome of a diagnosis system by using modern tools and methods. Diagnosis systems' design is a complex task where engineers in areas such as diagnosis design, systems design, modelling, LSC, availability and system safety etc. should gather and form a team. However, both the aviation and the automotive markets show that health monitoring systems based on diagnostics and prognostics are up-coming features that are here to stay and well worth to focus on.

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