Operational Risk Assessment for unmanned aircraft vehicles by using structural health and event management

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Abstract

UAV / UCAV will always be operated in a system of system scenario in order to achieve the highest possible mission effectiveness. Mission availability and reliability are the key elements and absolutely essential. Moreover, availability is a prerequisite to avoid mission delays or even mission interruptions – from an economical point of view availability helps to safe mission costs.

For this reason new concepts and technologies are required to determine the operational and aircraft safety risk to perform the next mission or in terms of an unscheduled event to perform a risk assessment to continue or to abort the current mission.

The present paper intends to discuss the operational risk assessment in context of the required structural health monitoring capabilities as part of an integrated health management system.

The discussion will be focused on the following main topics:

- Operational Requirements related to maximise mission availability.
- Integration Requirements
- Structural Health Monitoring System Design Concept related to the
  Aircraft Structural Integrity requirements

INTRODUCTION

Fatigue of aerostructures has been an issue since the early 20th century. Once accumulation of damage resulting from cyclic loads could be proven to be valid, aircraft were specifically designed such that they would withstand the loads for a defined life without visible cracks or damages. Progress achieved in fracture mechanics has been then taken advantage of in a way such that damage (e.g. cracks) can be allowed to be present in the structure, as long as its propagation can be controlled. This has led to lighter weight design, which is always a major design driver for aircraft but has also required more and scheduled inspection to be done over the aircraft's operational life. The balance between gain through lighter weight versus loss resulting from enhanced inspection effort has still been positive with regard to direct operating cost (DOC). This is roughly speaking the way aerostructures are handled nowadays with respect to their integrity. There is a well established design and maintenance procedure for all this, which has resulted in codes of practice, procedures and handbooks having

been established and improved over decades [ATA 2005; HSB 1995; http://www.esdu.com ; MIL-Handbook 5: http://www.mmpds.org].

Nowadays with the increased performance of military aircraft and the use of new materials in flight damages or structural overloads may not be detected using standard procedures and use additional structural health & usage monitoring capabilities to ensure the aircraft safety for the next flight.

With entering of unmanned air vehicles into service questions are raised whether the same design principles can be applied in the absence of the human sensor who is still able to recognize anomalies e.g. FODs.

There are different ways on how to approach this issues but one common answer is likely that more information regarding the aircraft's structural behaviour and condition state is required. Three possible options should be taken into account which are:

- go into the analytical procedures that allow calculation of damage accumulation and thus consumed life in a much more appropriate way or
- give much more frequent and thus relevant information on the current damaging stage of the aerostructure compared to the way inspection is done nowadays or
- allow monitoring of areas which are selected as critical due to fatigue, FODs or damages.

The dynamism in sensor development these days which among others can be observed in terms of miniaturisation, performance and price, combined with the remarkable progress achieved in sensor signal processing through mushrooming computation power and advanced algorithms has brought in a new wave of structural technology development that can be entitled as structural health monitoring (SHM). New and further sensors will allow monitoring of operational loads at various locations on the aircraft in much more detail which will further allow calculation of consumed operational life much more according to the real usage. This will be supported by high detailed loads and finite element models which allow an accurate loads calculation based on standard flight parameters. Further to this there is now more and more sensors emerging that allow monitoring of damage on structures in situ and where information can be retrieved at virtually any time, possibly

even on a wireless basis. This definitely can help to avoid a large amount of dismantling and re-assembly, which is normally required to access damage critical areas for simply obtaining the information 'No damage found'. As well as a condition awareness can be provided which is link to the operational-, or mission planning. This capability will lead to the capability to determine the operational risk which will improve the mission efficiency and aircraft availability and ensure the aircraft safety requirements.

Advanced Aircraft Structural Health Monitoring

The way aircraft are monitored today has not very much changed over the past decades. Most of the monitoring is done by visual inspection supported by other non-destructive testing techniques (NDT) such as ultrasonics and eddy current. Monitoring is done at prescribed intervals which are defined by the weakest links in the aircraft system. As a consequence a huge amount of information is generated, which needs to be processed directly by the maintenance personnel involved. In close to 100% of the cases the information is always the same: 'No damage found'. Further to this, the major effort in achieving this information is related to dismantling and reassembling the aircraft structure to get the respective access to the component considered. Is this huge amount of effort required to get such little of information? Are there no easier means to obtain this information in a more efficient way? In many cases we even replace the component with no sign of damage only because we do not consider any means to receive more continuous information from these components. For unmanned aircraft it is strongly recommended to change this philosophy and implementing new maintenance strategies which contribute to reduce operation and support cost and improves aircraft availability and mission reliability. Hence, for a safe and affordable operation of unmanned air vehicles a new design approach shall be taken into a account based on "Advanced Aircraft Structural Health Monitoring and Management". The following main features are taking into account:

- Integrate sensors into the structure that will give us more efficient information than we have today.
- Consider low-cost but reliable sensors which can be integrated into structures and providing sufficientproviding sufficient redundancy.
- Enable to process the high quantity of information generated.
- Justify the reduction of operation and support cost through new maintenance concepts.
- Enable the integration of sensor and acquisition of data into an integrated vehicle health management.
- Provide prognostic capabilities allowing a pro-active maintenance management
- Provide reliable decision support capabilities at different level of operations.
- Replace the pilot detection and assessment capability in case of specific in flight events to fulfil the relevant certification requirements

Structural health monitoring (SHM) is considered today to be the integration of sensors into structural components that allow continuous monitoring of the structure combined with automated advanced signal processing. To keep consistency with established designs in engineering, SHM is based on the engineering design principles applied nowadays and tries to automate and extend the monitoring process to the benefit of the engineering system considered. It uses sensors such as optical fibres, piezoelectric elements, micro-electro-mechanical systems (MEMS) or possibly even nano-structures to just name some of the ones being mentioned most. These sensors allow monitoring of strains, acoustics, electrical fields, temperature, pressure, humidity, chemicals and possibly more. Information is retrieved either by wires but more recently even wireless. Sensor signals are processed using advanced data-acquisition cards and multiplexers combined with FFT-analysers, wavelets, genetic algorithms and artificial neural networks to again just mention a few.

What could be monitored?

Since design principles in engineering are very much established and monitoring is just a consequence from all this, the central question with regard to monitoring results in: What are the design parameters which we have to assume in design and which we are thus most lacking, with regard to improve operability and cost effective design?

All structural design is based on loads (static as well as cyclic) which we have to assume prior to configuring the structure. These loads do not have to be limited to mechanical loads only. They can also include other environmental loads such as temperature, humidity, chemical corrosives, etc.. To improve the diagnostic, prognostic and decision support capabilities we require more information on when which load occurs (i.e. the real load sequence), about the damage characteristics and location etc.. This would allow us to manage operability more efficient without compromising safety. The means being required here is therefore *Loads Monitoring*.

The other phenomenon that needs to be monitored and which is a consequence from our design is damage. Damage needs to be monitored because:

- Operational loads as well as material properties are subject to scatter, which as a consequence can influence the incident of damage initiation as well as the period of damage propagation significantly,
- Loading of the structure can go beyond design allowables (overloading) either by accident or intentionally with respect to enhancements or life extensions,
- Damage is allowed to occur in a controlled way (fail-safe and damage tolerance).
- Unexpected damages can occur in case of in-flight events, FOD or incorrect handling
- Critical damages may not be visible at new materials (CFC…)
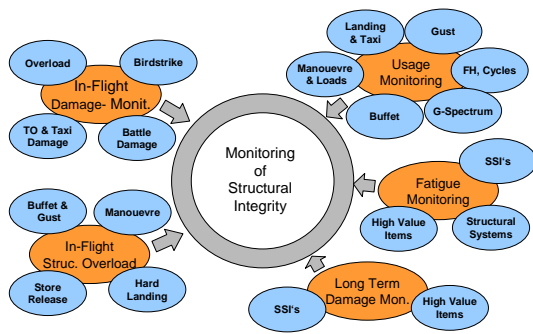
Figure 1 Operational Parameter

Today this is solved by large and obviously also costly inspection initiatives, where the cost could be reduced through automation without compromising safety. The means therefore considered here is *Damage Monitoring*.

Recent development in sensing and sensor signal processing technology gives rise to what has been and could be done for the enhancement of loads and damage monitoring and is thus summarised in the following.

Loads Monitoring

The way loads are currently monitored in aircraft is either by implementing strain gauges at well selected locations or using the flight parameters monitored on the aircraft. In both cases, either strain gauge or flight parameter based, the information recorded and downloaded on the ground is fed into a digital model, which is mainly the loads model of the aircraft structure on a FE basis. This load information can then be used to virtually calculate the damage accumulated at any location of the aircraft structure. The problem with the current loads monitoring systems is however that loads are monitored at fewer locations than this should be with respect to the aircraft's complexity. The Eurofighter Typhoon's structural loads are monitored with just 16 locations (strain gauges based or flight parameter based) being implemented over the whole structure of the aircraft. The major driver for that limited number of sensors locations have been restrictions in data gathering processing and storage and processing. However these decisions were taken in the past with the respective technology of that time. In terms of technology being available nowadays, this looks to be far too little sensing and any further improvement loads monitoring may be able to achieve has to be seen in the context of:

- Clear identification of the areas (e.g. notches, joints, lugs, fittings, etc.) of the structure being prone to damage;
- Monitoring of the load sequence in or very close to the areas being prone to damage, not even in a single but also on a multi-axis basis such that the load sequence provided is similar in quality to a load sequence having just been measured in the notch to be monitored.
- Monitoring of dynamic loads and the structural responses with respect to buffet overload and low cycle fatigue

The former can be achieved by a clear structural analysis. Current software analysis nowadays allows the mapping a structure with respect to stress and strain concentrations, as well as damage having been accumulated. The result is some colourful pictures of which an example is shown in Fig. 2. These pictures together with the results of highly representative structural tests allow down-selection and decide upon the locations worth to be monitored with regard to their load sequence that is
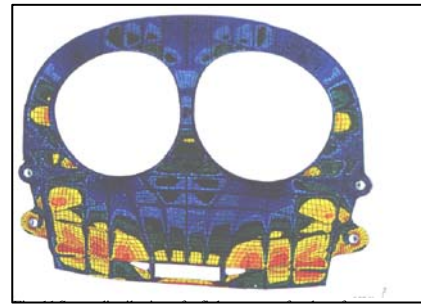

Fig. 2 Stress distribution of a fighter centre fuselage frame

then either fed into a FE analysis and a follow-on fatigue life calculation.

In addition these analysis allow also the identification and categorisation of the most critical locations simulating real structural overloads or in-flight events.

One of the limitations in using electrical strain gauges for strain monitoring is their relatively high amount of wiring. Two wires are required for each sensor. A much more elegant method in monitoring exists with fibre optic sensors and here specifically with fibre Bragg grating (FBG) sensors. These sensors have the advantage of being light weight, having all passive configurations, low power utilisation, immunity to electromagnetic interference, high sensitivity and bandwidth, compatibility with optical data transmission and processing, long lifetimes and low cost (as long as using silicon fibres). Their disadvantages mainly appear when being integrated into a material such as a composite where repairability of the sensor is mainly excluded. The overwhelming advantage of FBG sensors is however that they can all be lined up as hundreds and even thousands of sensors along a single optical fibre and can still be identified each due to their different grating pattern and thus be multiplexed. The applicability of this method not yet sufficient proven to integrate on real aircraft structures.

FBG sensors have a further advantage that they are able to also monitor temperature as well as pressure. With temperature and pressure profiles even being able to be recorded this allows to get a broader picture of a structure's loading environment. For the technology readiness level should be monitored and evaluated with regard of the potential to integrate them into an integrated health management system.

Damage Monitoring

Damage is monitored by non-destructive means. Conventionally this requires dismantling of most of the

structural system since most of the areas prone to damage are very much hidden and thus difficult to access. It is therefore more dismantling and reassembly which cause the relatively large effort for inspection when compared to the monitoring effort for finding the damage itself with an NDT technique. Sensors fully integrated or adapted to the structure to be monitored, that remotely send out the monitoring signal upon request can therefore help minimise the current dis- and reassembly effort required to the situation where damage is truly detected and repair is unavoidable.

To find out where sensors may be useful for integration and where sensors can be avoided, the stress distribution map such as shown in Fig. 1 and specifically a damage distribution 'map' of the structure based on simulations of realistic events, test results and expierence, is required as the first step. Further to this, any recordings from scheduled maintenance planning is essential to take into account underlining of the analytical results or extension of the information pool.

Monitoring even with structure integrated sensors can be done on the basis of a variety of different physical parameters. To keep compatibility with state-of-the-art NDT techniques in aeronautics, ultrasonics and Eddy current are the most popular techniques.

Ultrasonic and thus acoustic waves can be sent into structures by attaching and/or integrating piezoelectric elements to and/or into a structural component. Acoustic waves are sent out by the piezoelectric element where Lamb waves are possibly one of the most efficient since they operate as guided waves. The reflected and/or transmitted signal can then be again recorded by a piezoelectric element. Systems like this have been made commercially available such as the Smart Layer™ from Acellent Technologies [http://www.acellent.com] where piezoelectric elements are positioned according to structural needs on a Kapton Layer and are electrically wired by copper wiring using PCB techniques for the manufacturing process.

The acoustic waves emitted do not necessarily have to be sensed by piezoelectric elements. Fibre optic sensors will do it as well and here specifically FBG sensors catch up [Ihn et al., 2004]. This type of sensor will be specifically considered in areas where electromagnetic interference may be of concern or where other parameters may be useful to be monitored with the same sensor (e.g. strain or temperature). MEMS is another type of sensor that can be used in that context as well.

Current research is focused to evaluate the probability of detection capabilities, reliability and robustness of such systems which is an essential prerequisite to use them for damage monitoring of unmanned air vehicles.

After having discussed the principles of the loads and damage monitoring and the technology readiness level the following part of this paper is concentrated on discussing the top level requirements link to operation and support of unmanned air vehicles and the translation of them into the resulting structural health- and integration requirements.

Operational requirements

The R&D and acquisition cost of a UAV system are mainly dependent on the operational and support requirements, the development and production schedule of the system, the number of individual elements required in the architecture of the UAV system, the size, complexity and autonomy of the UCAV air vehicle, the technology maturity at development start, the certification and the international work share. Fig. 3 shows a busy picture which represents a generic approach to derive the operation and support requirements of an UAV.
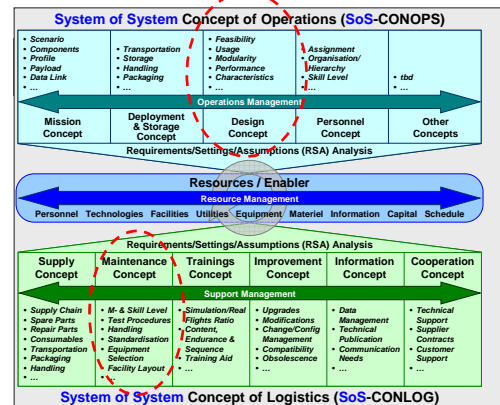

Fig. 3 Operational and Support Requirements

For UAVs the derivation of the operational and support requirements appears to be more complex since they will be operated in a network of systems and where the mission effectiveness is not anymore dependent on the readiness of one platform but from the readiness of all systems involved to perform the mission. For this purpose it is essential to design and implement a structural health management system that provides:

- Condition State Awareness
- Improved Diagnostics
- Prognostic and
- Reliable Decision Support capabilities
- sufficient accuracy, reliability and redundancy

to manage:

- Airworthiness requirements
- Structural Integrity
- Operational Risk
- Maintainability and Supportability
- Operation-, Support- and Mission Cost.

A well defined set of requirements and the translation of them into design- and functional health management requirements is an essential pre-requisite for a successful development and integration.

Conceptual Approach

One definition of Structural Health Monitoring (SHM) is the resident monitoring of structures/components by means of sensors integrated or applied to the structure.

The aim of the Load / Usage Monitoring System is the calculation and / or measurement of the loads (deflections, temperature, strains and subsequent loads) during operation. Such usage monitoring systems serve as data basis for real loads acting on the component to

be monitored during operation and reduce the uncertainties of the operation scenario models. To guarantee availability and operability the operator needs condition awareness to make decisions throughout the whole mission. Related to the monitoring of the structural strength capability of the aircraft the loads monitoring will provide the relevant details for example by comparison of the expected load against the measured loads, as basis for the real time assessment of the aircraft condition. In addition for the fatigue life monitoringTherfore, accurate models for the prediction of the onset and growth of damages and the remaining life of the components are required. Especially in case of composite structures these models have lot of uncertainties due to the high amount of influencing factors like production and handling procedures leading to high safety factors.

The aim of the Damage Monitoring System is the determination of the damage (Type e.g. fatigue crack growth in metals or impact delaminations in composites, Location and Size) during operation.
The combination of both systems together with a reliable materials model with the real load history and actual damage distribution as input data should lead to by far more accurate predictions of the structural strength and the remaining life of the component and subsequent to optimized and individual tuneable inspection / repair strategies.

An integrated System consists of several components that have to communicate with data management platform. The following described approach is based on the OSA-CBM standard which is on open system standard for condition-based maintenance. The OSA defines and gives structure to the types of information found in a condition monitoring system, The OSA-CBM standard also defines how that information is moved around. OSA-CBM is a communications framework for next-generation machinery monitoring and diagnostic systems.

Figure 4 describes the functional concept of the OSA-CBM standard. This paper can not discuss the detail of the OSA-CBM standard and therefore we would like to reference the OSA-CBM website http://www.osacbm.org/.

Since the completion of the program in 2003, OSA-CBM has been merged in MIMOSA consortium.
The following areas are covered by the this standard:
- Functional architecture design according to the layers of ISO 13374 standard.
- Protocol guidance for communication between software applications.
- Data architecture design based on the CRIS data model from MIMOSA.
- Implementation guidance among available middleware technologies.

Figure 4. Functional Concept

Functional model

Functional model is compatible with layers defined by ISO 13374. All layers have a UML and a XML model, except Decision support and Presentation layers, because they are specific to each maintenance application.
It is important to be aware that OSA-CBM provides UML and XML models for each layer and defines relations with the CRIS data model (e.g. the DA layer can provide various forms of data including single data, sequence data, waveform data , BLOB data, etc…).

Communication policies

The OSA-CBM communication policies are based on client/server and pull-based communication model. Generalisation of pull communication model is too restrictive for communication on-board aircraft, where communication model is generally based on push-communication model with some pull communication adaptation at centralised level (e.g. avionics data services of ARINC 763 or Avionics Broadcast Data Collector protocol).
Therefore it is more appropriate to perform locally DA, DM, (CM) and then push XML formatted date over UDP/Ethernet to the data management platform
The capability to use OSA-CBM communication service over Air/Ground communication service has still to be verified.

Why should we select the OSA-CBM standard

It has to be assumed that health monitoring will be performed with various types of sensing system. Today we can conclude that no sensing system is available on the market that fulfil the requirements. It is very likely that this will not changed in future.
Switching from one sensing system to an other sensing system should not make a difference on what the end operator is presented in terms of information. The OSA-CBM structure enable to fulfill this requirement.
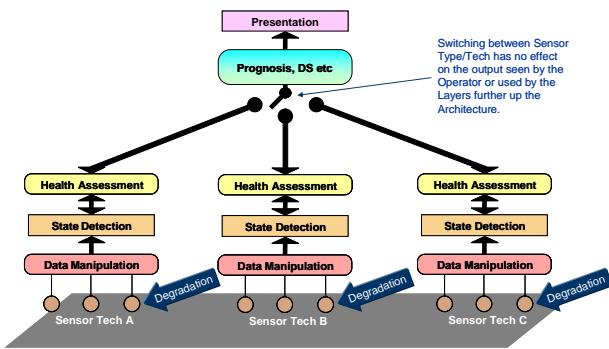
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**Fig. 5 Technology Independence Functional Diagram-
different sensor types/technology**

Fig. 5 shows an example, the technology being varied is
down at the sensors. Variation in data type or format may
occur below State Detection, but at Health Assessment,
even though the assessment algorithms may be written
differently to cope with the slightly different inputs, above
this level, it should not matter what technology was used.

Figure 6 shows the proposed architecture for integration
of structural health monitoring and management which is
OSA-CBM compliant.
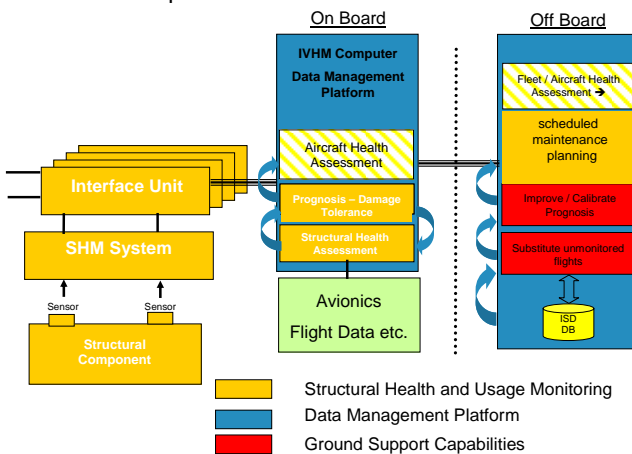
Fig. 6: Proposed Health Management Architecture.

The architecture can be grouped into three main
elements:

- Component Level
- On Board Health Assessment and Management
- Off Board Health Assessment and Management

Component Level

Sensor
The most important component is the identification of the
relevant kind of damage depending on the material and
load and its impact on the performance of the component.
With metallic structures, designers and operators are
mostly concerned with fatigue cracks and corrosion, while
for composite materials, delamination and impact damage
are more of a concern.

Computation

Several processing units are necessary to operate a SHM
system. On the local level, a processor must interface
with the sensors to acquire the data and convert the raw
analog signals to digital ones. If it is an active system,
such as with Lamb wave methods, the processor must
send instructions or waveforms to the actuator
periodically. Data rates between 25 and 50 Megabytes
per second would be necessary for each Lamb wave
sensor collecting data in the system or 0.5 to 1
Megabytes per second for acoustic emission sensors. At
these rates, it can be seen that a large data storage
capacity is required.

Power

Most of the components mentioned in the previous
sections require power to function. Piezo actuators, for
example, operating actuating at 15 kHz with 5 V peak-to-
peak would draw 24 mW each. A low power
microcomputer to process the data would likely draw
about 10 mW, and a short range wireless device would
require about 5 mW to function. Although the individual
component power demands are low, this becomes
challenging when there are many components distributed
throughout the surface of the structure, some of which
can even be embedded within the skin. Power could be
supplied locally by batteries, or provided from within the
vehicle via an electrical bus. Some researchers have
proposed systems where energy is transmitted by radio
frequencies to inductive loops, or collected passively with
harvesting devices to the local sensor and processing
patches. In case of airworthiness relevant systems the
power supply has to fulfil a high degree of reliability,
stability and redundancy.

Onboard

The health assessment and prognostic layer will be
hosted in the data management platform. Which means
the algorithm for diagnostic and prognostics will request
the data from the state condition layer and compute the
condition change.

Algorithms are probably the most essential component to
a SHM system. They are necessary to interpret the
collected data, and require an understanding of the
operational environments and material thresholds.
Due to the high requirements on the qualification of
onboard systems regarding reliability, accuracy and
airworthiness the onboard functionality needs to be
selected considering the following main items:

- Ensuring in-flight safety
- Change of functionality not expected
- Increase turn around time
- Essential for subsequent offboard analysis

Offboard

For the development of the health management system
UAVs diagnostic and prognostic capabilities shall be
provided to the onboard data management platform
considering the above requirements. Additional diagnostic
and prognostic capabilities, which not have to be
mandatory available during flight, could be part of the
offboard system together with the necessity to consider a

loss of data which requires a substitution capability and re-calibration capability of the algorithm.

Operational Risk Assessment

The first stage represents collecting and manipulating data and making a state detection assessment (identification of the relevant kind of damage depending on the material and load and its impact on the performance and safety of the component) and a Health Assessment (are the component serviceable and how much remaining useful life is left. These operations address the first 3 layers of the OSA-CBM architecture.

To estimate the current damage and health status of the structure,, the following operational data are taken into account:

- Loads
- A/c all up weight
- Landing velocity
- etc.

The mapping of these input parameters to the estimation of damage is carried out using a physical based model and data. Algorithms are probably the most essential component of the health assessment layer. They are necessary to interpret the condition state, and require an understanding of the operational environments and material thresholds. The remaining useful life can then be calculated in FH be mapped to a quasi-RUL. These RUL predictions are based on certain assumptions of expected usage (that may vary from fixed 'normal' conditions to parameterised RUL predictions were parameters indicate expected usage.

A last step involves a final confidence calculus where different RUL models with associate confidence levels may be computed. A simple calculus may apply with a single RUL prediction as a consequence of expected usage:

Expected usage (A) * RUL Confidence (Exp. usage A)

There may be also a combination of models, where mission plans may lead to different probabilities concerning expected usages (i.e different models taking into account different usage parameters)

Probability (exp. usage (A) * RUL Confidence (exp. usage A)
+
Probability (exp.usage (B)) * RUL Confidence (exp. usage B)
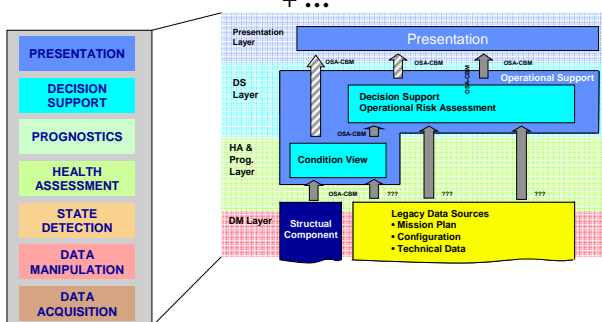***+ ...***

Fig. 7 Operational Risk Assessment

Airworthiness and Certification Aspects

In the past SHM systems have been used to monitor the theoretical fatigue life consumption as basis for fleetmanagement and scheduling of inspections and modifications. Due to the used safety factors and scatter factors the implication on the day by day airworthiness was a secondary factor.

With the development of high performance aircraft the airworthiness issue becomes more significant for the post flight assessment regarding an intact structural strength capability.

Nevertheless the identification, assessment and decision in case of an in-flight event like a birdstrike, lightning strike, battle damage or damage during taxi or landing FOD, relies always on the pilot.

The absence of a pilot requires additional highly advanced in-flight capabilities of UAV SHM systems to take over the responsibility for the above mentioned items an others.

Discussions within the United States about future topics which require increased attention and new developments identified the following items, which directly influence the requirements on UAV SHM systems:

- Reduction of UAV mishap rates
- Integration of UAV's into national / international aerospace outside of restricted areas

These two items identify the necessity of an onboard real time loads monitoring and damage detection system with a subsequent diagnosis and health assessment functionality to check after an in-flight event the structural strength capability and structural performance.

Therefore beside the attractive function to reduce direct operating costs and life cycle costs, UAV SHM systems have now to fulfil aircraft safety requirements to cover the above challenges.

This will lead to increased demands for reliability, accuracy and redundancy, for which sufficient evidence and qualification has to be provided to fulfil the relevant certification level.

The following chart shows the top level process and related requirements on an in-flight SHM event monitoring function.
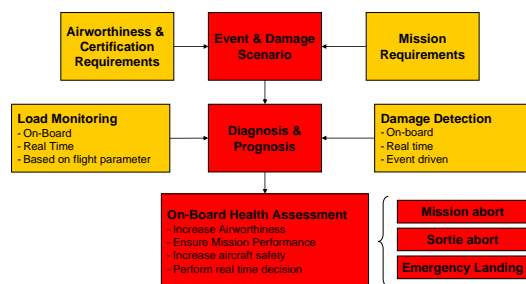

Fig. 8 SHM Event Monitoring Function

These new requirements on certification and functionalities will result into new SHM system design principles and qualification processes.

SHM Design Process

The SHM design process, which consist of the following steps:

- Definition Phase
- Design Phase
- Development and Qualification Phase
- Usage Phase

is mainly influenced by

- Aircraft Type
- Operation Scenario
- Mission Variability and Area
- Usage Requirements
- Affordability
- Reliability
- Certification Philosophy and Safety Factor's
- Aircraft detailed Design and Interfaces
- Aircraft & Component Qualification

In specific the Definition Phase is a very important part of the design process, as this phase shall define the top level requirements for the

- Event Monitoring
- Damage Monitoring
- Load Monitoring (incl. Dynamic Loads)
- Usage Monitoring
- Fatigue Life Monitoring
- Critical Areas

based mainly on the aircraft type, operation scenario and mission performance.

The following matrix shows as example the main functionalities of the various SHM subsystems as result of an initial design review.

	In-Flight Damage Monitoring & Assessment	In-Flight Structural Overload Monitoring	Usage Monitoring (UM) & Fatigue Life Monitoring (FLM)	Long Term Damage Monitoring
ISR Long Distance, High Altitude	Birdstrike	G-Monitoring Hard Landing Monitoring	Usage Monitoring Gust, FH, Cycles	Single Cases
ISR Short D., med. to low altitude	Birdstrike Battle Damage	G-Monitoring Hard Landing	Usage Monitoring G-Spectrum, Gust, FH, Cycles	Single Cases
Strike / Suppr. of Enemy Defense	Birdstrike Battle Damage	G-Monitoring Hard Landing Store Release	Extended UM Dedicated FLM	Dedicated areas Manoeuvre Loads Low Cycle Fatigue
Electronic Attack and Combat	Birdstrike Battle Damage Structural Overload Damage	Manoeuvre Hard Landing Store Release Buffet	Extended UM Dedicated FLM	Dedicated areas Manoeuvre Loads Low Cycle Fatigue

Fig. 9 Example of Definition Phase Result

During the design process enough system flexibility has to be considered to cover upgrades and modifications requested within the usage phase of the SHM-system.

Conclusion

SHM related technological development and integration described above is far from being at the limits. There is a variety of further materials and signal processing threats along the technology development road. The discussion shows that UAV's will need additional SHM functionalities

to fulfil the relevant airworthiness and certification requirements. However as long as benefits of SHM have not been clearly evaluated and communicated, pursuing these threats may not be much worth to be done. Much consideration will however be required to get the sensing and actuation devices attached onto or integrated into the structural material in an appropriate, reliable and cost-effective way. Nevertheless the definition and design process for the selection of the SHM functionalities for a new UAV with specific mission requirements is very important to optimise the ratio between development cost and life cycle cost. Further threats can be seen with respect to providing energy to the respective elements. This will become specifically important if wireless communication is considered. Will batteries be required or can the system charge itself through energy harvesting from the structure? Wireless technology will play another important factor with increasing numbers of sensors and this becomes more and more relevant when size and cost of the sensors decrease. Such technology will further promote development of smart sensing coatings that can be easily integrated into or attached onto the structures to be monitored. The following table compiles one of the top level requirements to integrate SHM into the IVHM system of an UAV.

Onboard Health Monitoring System	
The on-board Health Monitoring shall cover: Data Acquisition (DA), Data Manipulation (DM), State Detection (SD), Health Assessment (HA) and Prognosis Assessment (PA) for Aircraft Systems	The on-board Health Monitoring system monitors the current health and predicts the future health of the system being monitored. Within the OSA-CBM stack this is the Data Acquisition to Prognostic Assessment layers.
The on-board Health Monitoring system shall provide data/information to the Health Management System, in accordance with and as defined by the OSA-CBM interfaces.	Health Monitoring is compliant with OSA-CBM and therefore passing correctly formatted data up the OSA-CBM stack
Each of the on-board Health Monitored component / equipment and systems shall use domain specific expertise/knowledge Health Management shall cover at priority components, systems and structural parts that are considered significant drivers from an operability point of view.	It is recognised that the optimum design and implementation of the Health Monitoring system will be highly dependant on the application domain, with each domain having their own specific design requirements
Global time stamping of data shall occur at the earliest possible opportunity	To allow data fusion and appropriate analysis to be conducted on data from multiple sources

Data Aquisition & Data Manipulation	
Data Acquisition shall have minimal impact upon the power consumption, weight size, reliability and operation of the component, equipment or system being monitored.	The greater the transparency and independence the greater the benefits
Transducers shall be capable of operating within the specified aircraft environment	Essential environmental constraint
Monitoring technologies shall support the information exchange between the Maintenance Applications within the prescribed OSA-CBM model.	
Data Manipulation may include fusion of data from 2 or more transducers	The DM functionality may need to combine data from distributed sensors covering an individual component, sub-system etc in order to provide the correct data for SD to be performed

State Detection	
State Detection shall provide outputs in compliance with OSA-CBM	Ensures the system meets the requirements of the OSA-CBM standard
State Detection shall provide a data confidence index	Allows an objective assessment of the SD output to be made, and will provide additional information to higher level functions
BITE message is generated at State Detection	Ensures any equipment generating BITE messages integrates into the OSA-CBM architecture

Health Assessment	
Health Assessment will be performed at component / equipment, system, and aircraft levels	The HA needs to cover all levels from component to aircraft (and maybe Fleet) to allow a detailed and complete assessment to be made
In all possible cases the efficiency of Diagnosis shall be increased by use of information provided by Prognosis and more generally by Health Management.	Improve the efficiency of Diagnosis due to additional information related to the actual status of some operability-driving components.
Health Assessment may use specific or generic algorithms	Allows both generic and specific algorithms to be used. This means both platform dependent and independent systems may be developed.
Diagnostic technologies shall support the information exchange between the Maintenance Applications within the prescribed OSA-CBM model.	
The Diagnostic function shall provide relevant information to other functions in accordance with the prescribed information exchange.	