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A STUDY ON SYSTEMS HEALTH MANAGEMENT AND THE PRIORITIZATION OF FUTURE REQUIREMENTS: A SAFETY PERSPECTIVE

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ABSTRACT

A health management (HM) system is responsible for information gathering about a system's health and corresponding decision-making. HM systems are typically used to identify any degradation in performance that may affect safety or successful operations of a system. Effective long term development of successful health management solutions requires an improved understanding of the relationship between potential adverse events that may happen during flight, and validated tools, technologies, and techniques developed for mitigating their negative effects on system safety and functionality. This paper presents a study on the assessment of future requirements for systems health management technologies and related research areas, and the results of a casual factor analysis based upon a systematic study of aircraft accident and incident data. The gist of the paper is the mapping between SHM technologies and causal factors developed with the goal of prioritizing future SHM requirements in order to improve safety margins. The goal of the study is to identify key research areas in systems health management and to recommend specific technology needs to support the development of integrated system health management tools, technologies, and techniques that will address safety related challenges facing current and future aircraft systems.

1 INTRODUCTION

A health management (HM) system consists of instrumentation components, fault detection, isolation and response module, diagnostic and prognostic software, as well as processes and procedures responsible for information gathering about a system's health and corresponding decision-making [1-4]. HM systems are typically used to identify any degradation in performance that may affect safety or successful operations of a system, and to identify the specific subsystems that require maintenance or response to restore full operational capability [5]. To achieve these goals, a health management system constantly monitors the health of a system and responds to potential problems by enabling system reconfiguration or restoration, maps anomalies to physical components that have failed during operation, and predicts physical components that are likely to fail in the future. Health management systems, when implemented successfully, hold the promise to significantly improve safety, reliability, affordability, and sustainability for aeronautic systems.

Recognizing the importance of systems health management (SHM) as an integral part of aeronautic systems' functionality,

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NASA's Aviation Safety Program is investing in systems health management through the Integrated Vehicle Health Management (IVHM) project [6]. This project seeks to develop validated tools, technologies, and techniques for automated detection, diagnosis and prognosis that enable mitigation of adverse events during flight. The project also includes a systems analysis aspect that; 1) *assesses technology and research requirements related to SHM*, and 2) *documents information about causal factors in aircraft safety incidents and accidents as they relate to the key research areas in SHM*.

As part of these efforts, this paper presents a study on the assessment of future requirements for SHM technologies and related research areas, and the results of a casual factor analysis based upon a systematic study of aircraft accident and incident data. The gist of the paper is the mapping between SHM technologies and causal factors developed with the goal of prioritizing future SHM requirements in order to improve safety margins.

The goal of the study is to identify key research areas in systems health management and to recommend specific technology needs to support the development of multidisciplinary integrated system health management tools, technologies, and techniques that will address safety related challenges facing current and future aircraft systems.

The remainder of this paper is broken up into six sections. Section II gives background on recent studies on establishing research requirements for SHM. Section III talks about the results of a survey conducted to define key research areas for SHM as related to NASA's IVHM project. Section IV summarizes the results of a causal factor analysis in aircraft safety incidents and accidents. Section V presents the mapping of causal factors to SHM research areas, followed by a prioritization of SHM research areas in Section VI. Finally, Section VII provides discussion and summary, respectively, of the topics in this paper.

2 BACKGROUND

In recent years, a number of studies have been conducted by subject matter experts that documented key research areas for improving SHM capabilities [7-12].

The Decadal Survey of Civil Aeronautics conducted a comprehensive review of the current aeronautics technologies and has put forth 51 highest priority R&T challenge areas [7], which includes 6 SHM technology development areas are among the highest rated challenges.

The National Institute of Aerospace has conducted a comprehensive study to identify and document research and technology challenges for improving aviation safety for future air transportation systems. The plan contains four technology thrust areas one of which is defined as "health and reliability management" [8]. This report outlines 10 HM technology areas, which are discussed later in this paper and included in the subsequent mapping analysis.

MacConell [9] performed a study in order to define overall scope and key research areas in System Health Management. This study [9] identifies a set of 40 potential capabilities made possible by an idealized SHM system. These are categorized based on their potential in providing three functional characteristics of an SHM system: "mission availability", "mission success", and "mission capability". In addition, "design paradigm" is defined as a fourth category against which SHM technologies can be classified.

Another resource that documents technology trends and needs in SHM is the Joint Strike Fighter (JSF) Program, which is currently the best developing example of a highly integrated system for health management [10]. Similarly, the Air Force Research Labs (AFRL) published a list of prioritized engine health monitoring technologies [11-12].

This study leverages from these prior efforts and builds upon them by bringing experts together in order to reconcile the development of SHM research needs and requirements. These experts come from a wide range of disciplinary backgrounds (airframe, avionics, propulsion, etc.) and represent major stakeholders within the NASA's IVHM project [6].

3 ESTABLISHING FUTURE REQUIREMENTS FOR SHM RESEARCH

The first objective of this study is to provide input for future requirements for SHM research. This section contains the results of a survey performed to achieve this objective.

The results of our survey list 25 SHM technology requirement areas, which are reconciled through the review of the aforementioned documents [7-12] and the assessment of SHM experts within the NASA IVHM project.

The technology requirement areas are determined and organized based on the high level objectives of the Integrated Vehicle Health Management (IVHM) project [6], and are grouped under one of the four major thrust areas of the project: "detection", "diagnosis", "prognosis", and "mitigation".

In this paper, we simply provide a list without any grouping. Where appropriate, we have provided examples of established or new technologies addressing particular requirements, and respective references from the literature. The SHM technology

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requirements list includes:

1) Gas Pressure Measurement Technologies: Multifunctional pressure measurement technologies for turbine engine test validation [11-12].

2) Surface Measurement Technologies: Surface measurement technologies are critical in propulsion system research. The sensors include those for strain, temperature, heat flux and surface flow which will enable critical vehicle health monitoring and characterization of components of future space and air vehicles. Various solutions include thin film sensors, over wire and foil sensors [11-13].

3) Strain Measurement Technologies: Novel strain measurement technologies offer advantages over traditional wire and foil strain gages in service temperature, on conductor size, on service life, and on installation speed and ease. Examples include embedded strain sensors enabled by direct wire thermal sprays, thin film sensors, and fiber-optic strain sensors [11-12, 14, 15].

4) Harsh Environment Sensor Technologies: Many aerospace systems and components operate in harsh environments. These components operate routinely and continuously under extreme thermal and mechanical loading. Such conditions promote yield, fracture, fatigue and creep, which accelerate structural wear and eventual failure. Sensory technologies developed for harsh environments include piezoresistive sensors, fiber-optic MEMS sensors, and SiC sensors [16-22].

5) Fluid Leak Detection Sensor Technologies: Fluid systems abound on aircraft. A leak is an indication that either tubing or seal integrity is compromised. Loss of excessive fluids results in overheating, loss of system performance, or catastrophic failure. Sensor technologies, which can detect fluid leaks, hold the promise to improve safety by allowing early detection of fluid leaks [8].

6) Lightweight, Low Power Load Sensor Technologies: Technologies that allow an airframe to be networked with many sensors and loads measurements that can be fed real-time into an on-board model for airframe health monitoring [6, 8].

7) Self-Powered Wireless Sensor Technologies: Enabling technology that could eliminate the need for batteries, and extend the useful life of sensors in a variety of aerospace applications [9, 11-12, 23-26].

8) Crack Detection/Monitoring in Blades and Disks: Crack detection technologies for blades address the need for a real-time monitoring system capable of early identification and prevention of safety-significant malfunctions of the propulsion system of operational engines. This includes engine health monitoring for broken missing blades and foreign object damage, as well as center-of-mass crack detection [11-12, 27-28].

9) Blade Tip Clearance Monitoring: Blade tip clearance control is one of the main parameters governing turbine efficiency. Large clearances lead to rapid efficiency drop off, low clearances lead to the risk of rubbing, or even catastrophic failure. Blade tip sensors such as eddy current, capacitive and optical offer new technologies to detect engine faults [11-12, 29].

10) Oil Debris Monitoring: Rotating machinery and lubricated components exhibit wear-out failure modes. These failure modes tend to develop slowly as components wear. Particles expelled from bearings, gears, and bushings disseminate in the lubricant. These particles can damage other components by causing excessive abrasion and wear. Oil debris monitoring technologies can be used for analysis of solid particle contaminants within oil and other lubricants [8,10, 30].

11) Operational Load and Environment Monitoring: Technologies used for monitoring operating conditions and the environment in order to increase operations safety and reliability [8, 9, 31-32].

12) Thermal Barrier Coating (TBC) Health Monitoring: Thermal barrier coatings are highly advanced material systems applied to metallic surfaces, such as gas turbine or aero-engine parts, operating at elevated temperatures for insulation purposes. Technologies enabling the monitoring of TBC performance hold the promise of improving engine performance [11-12].

13) Bearing Health Monitoring: Bearing failures in the turbine engine not only result in damage to that bearing, but can also lead to extensive collateral damage within the engine. Thus, technologies for monitoring the health of bearings have been listed as a critical requirement for future SHM systems [9, 10, 33-35].

14) Engine Emission Monitoring: The monitoring of engine emissions is important for aero engine applications. Technologies that can be used for the calculations of combustor performance, engine thrust and ram drag among other quantities hold the promise of improving engine performance [11-12, 36].

15) Structural Corrosion Monitoring: Technologies that measure different aspects of electrochemical corrosion reactions are needed to detect and respond to material corrosion [6, 9].

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16) Remaining Useful Life Quantification: It is essential to know remaining useful life (RUL) of components for guarding against surprise and catastrophic failures. Numerous techniques exist including data-driven and model based methodologies for RUL estimation and new technologies are needed that better characterize RUL for a wider scale of component/system types [9, 37-39].

17) Digital Avionics Data Error Trending: Increased use of digital avionics is commensurate with new avionics architectures. This, technologies are needed to detect and trend data errors and to enable early removal of offending avionics before a hard failure occurs [8].

18) Prognostics for Rotating Machinery: Rotating machinery on aircraft includes all types of engines, motors, pumps, gearboxes, and turbines. Performance of rotating machinery is critical to systems operations, thus technologies are needed that can trend the performance of rotating machinery and predict actual failures and the remaining useful life (RUL) of components [6, 8, 9].

19) Intermittency Analysis/Characterization: Intermittent faults are a systemic problem in mature aircraft programs. In order to better manage intermittent faults, technologies are needed that provide information about the causes and next occurrences. Advanced algorithms should determine if the faults are caused by physical hardware damage and by what likely damage mechanisms [9, 40-41].

20) Power System Performance Trending: Power systems are among flight critical subsystems, especially in future aircraft architectures. Thus, technologies are needed to trend the power system performance and adjust to changing conditions [9].

21) False Alarm Filtering: False alarms in legacy aircraft diagnostic systems have negatively impacted fleet maintenance costs and mission readiness. Thus, technologies are needed to reduce false alarm rates [9, 42-43].

22) Composite Materials Damage and Failure Modeling: Composite materials promise lighter and stiffer structures. The percentage of composite airframe structural components is ever increasing. Thus, tools and technologies are needed in order to better characterize faulty behavior of composite materials [2, 8].

23) Integrated Avionics Cross-Correlation Modeling: The current state-of-the-art in avionics testability still exhibits a high percentage of false alarms. Thus, technologies are needed that would reduce false alarms and prevent inappropriate pilot decisions based on inaccurate avionics health [8].

24) Reconfigurable Power Systems: Power systems are among flight critical subsystems, especially in future aircraft architectures. Reconfigurability of power systems is important and required capability for future aerospace systems [6, 9].

25) PHM Design Standards and Education: As SHM technologies become more and more prevalent in commercial aircraft, the standards by which they are designed, qualified, and certified for commercial transports need to be defined and standardized [8, 9].

4 ESTABLISHING CAUSAL FACTORS AND DAMAGE CONDITIONS RELATED TO AVIATION SAFETY

The second objective of this study is to document the results of an examination of the most recent statistical/prognostic incident and accident data that is available to determine the causal factors of system or component failures and/or malfunctions in U.S. commercial aviation accidents and incidents. This section contains the results of an analysis that have been conducted by NASA to achieve this objective [44]. In this analysis, publicly available National Transportation Safety Board (NTSB) and Federal Aviation Administration (FAA) accident and incident data were examined. All these data sources can be found in the Aviation Safety Information Analysis and Sharing (ASIAS) System.

4.1 Causal Factor Analyses of NTSB and FAA Accident and Incident Data

The analysis was conducted to determine the causal factors of accidents and incidents associated with failures or malfunctions of the various systems or components of commercial aircraft during 1988-2003. In this analysis, "commercial" is defined as Part 121, Scheduled Part 135 and Non-Scheduled Part 135 flights. Non-impact fires were included as a type of malfunction, even when the cause of the fire was not specified. The safety risk is based on both accidents and incidents, which are defined as follows:

> *Accident* - an occurrence associated with the operation of an aircraft, which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage.
>
> *Incident* - an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations.

The source for accident data is the NTSB Aviation Accident and Incident Data System, while the source for incident data is

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the FAA's Accident/Incident Data System. Although both databases contain both accident and incident data, the FAA has primary investigative responsibility for incidents and the NTSB is the authority for accident investigation.

For each accident and incident, the system affected by the malfunction or failure was determined. In some events multiple systems were affected, and in these cases the first system affected was selected. For example, if an electrical malfunction preceded an engine fire, that event was categorized under Electrical. The result of these efforts is the "Adverse Events Table" presented in Table 1.

4.2 Adverse Events Table

The purpose of the Adverse Event Table is to provide guidance to the IVHM Project based on the aforementioned analyses. As the IVHM Project matures and future technologies and trends become clear, this initial set of Adverse Events Types and candidate examples may change. (An event is defined as either an *accident* or an *incident*.)

This first version of the initial Adverse Events Table is constructed by collecting data gleaned from findings within the ASRS and NTSB databases. The intent was to call attention to damage conditions that occur frequently while providing insight on their severity based on associated injury and fatality rates.

The adverse event types are categorized into five classes based on the overall remaining useful life of the affected system, subsystem, or component: *incipient failures*, *slow-progression failures, intermittent faults*, *cascading faults* and *fast progression failures* which are defined in the first column of Table 1.

Depending on the nature of the damage condition, there are scenarios in which more than one of these classes applies to a particular adverse event type. For example, a software fault could lead to a fast progression fault as in the case of a stack overflow, or a slow progression fault, as in the case of a memory leak. While acknowledging this, we have categorized each adverse event type based on the most typical progression behavior.

In addition to the number of accidents and incidents (column 3) data, a breakdown of fatalities and injuries are included in the fourth column of table. This additional information is not used in the subsequent prioritization and mapping analyses and is left as a topic for future studies.

Table 1. Adverse Events and Example Damage Conditions with Severity and Frequency [44]

Adverse Event Type	Example Damage Condition	Severity and (Frequency)	Fatalities and Injuries
Incipient Fault: Hard to detect and differentiate due to extremely slow degradation in performance	1. Icing conditions in propulsion system	1. Accident (6)	1. Fatalities (3) Injuries (21)
	2. Fault of power electronics -Power drivers -Power supplies -Switching transistors -Electronics packaging -Electronic circuit boards	2. Accident (11) Incident (185)	2. Fatalities (1) Injuries (50)
	3. Turbine engine bearings -Fatigue spallation	3. Accident (4)	3. Fatalities (0) Injuries (3)
Slow Progression Fault: Very hard to detect, gradual degradation in performance	4. Fatigue cracks on metallic airframe structure	4. Accident (13) Incident (605)	4. Fatalities (12) Injuries (107)
	5. De-lamination in composites	5. Accident (2)	5. Fatalities (0) Injuries (6)
	6. Ball-jam in EMA -Hydraulic actuator failures	6. Accident (18) Incident (657)	6. Fatalities (0) Injuries (58)
	7. A/C and pressurization faults	7. Accident (4) Incident (1247)	7. Fatalities (7) Injuries (40)
	8. Oil/lubrication system failures	8. Incident (246)	8. Fatalities (0) Injuries (7)
Intermittent Fault: Fault does not degrade but instead is a recurring hard fault that comes and goes, for example a signal conducted via a loose connector.	9. Wire chafing resulting in an electrical short due to an unexpected ground path	9. Accident (9)	9. Fatalities (0) Injuries (10)
Cascading Fault: Faults that may have a single root cause yet progress to create faults in other systems, subsystems, or components.	10. Power system faults resulting in wide-spread systemic issues -Electrical distribution problems	10. Accident (10) Incident (484)	10. Fatalities (233) Injuries (28)
	11. Aileron, rudder, or control surface (elevator) faults	11. Accident (22) Incident (996)	11. Fatalities (285) Injuries (9)
	12. Instrumentation, communication, and navigation	12. Accident (5) Incident (3208)	12. Fatalities (4) Injuries (21)
	13. Fuel system faults	13. Accident (20) Incident (278)	13. Fatalities (17) Injuries (49)
Fast Progression Fault: Limited precursor signature but rapid degradation	14. Engine stall/faults in turbomachinery	14. Accident (52) Incident (2424)	14. Fatalities (227) Injuries (407)
	15. Landing gear faults -Gear extension/retraction	15. Accident (97) Incident (1288)	15. Fatalities (5) Injuries (123)
	16. Brake/anti-skid system faults	16. Accident (23) Incident (286)	16. Fatalities (70) Injuries (0)
	17. Lightning and radiation related avionics faults	17. Accident (1)	17. Fatalities (0) Injuries (0)

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mitigating the effects of wire chafing problems, and has little or no relevance to turbine engine bearing faults.

Table 2. "Relevance" Mapping of Damage Conditions to SHM Technology Requirements

IVHM Technology Requirements and Needs	Icing conditions in propulsion system	Fault of power electronics	Turbine engine bearing faults	Fatigue cracks on metallic airframe structure	Delamination in composites	Ball jam in EMA/hydraulic actuator failures	A/C and pressurization faults	Oil/lubrication system failures	Wire chafing faults	Power system faults/Electrical distribution probl	Aileron, rudder, control surface faults	Instrumentation, communication, and navigation failure	Fuel system faults	Engine stall/Faults in turbomachinery	Landing gear faults	Brake/anti-skid system faults	Lightning and radiation related avionics faults
	Adverse Events																
Gas Pressure Measurement Technologies															0.888		
Surface Measurement Technologies	0.666			0.666	0.777												
Strain Measurement Technologies				0.888	1												
Harsh Environment Sensor Technologies			0.888												0.666		
Fluid Leak Detection Sensor Technologies								1						0.888			0.666	
Lightweight, Low Power Load Sensor Technologies				0.777	0.666												
Self-Powered Wireless Sensor Technologies	0.666		0.666	0.666								0.666			0.666	0.777	0.666	
Crack Detection/Monitoring in Blades and Disks			0.666												0.777			
Blade Tip Clearance Monitoring															0.777			
Oil Debris Monitoring			0.666					0.888										
Operational Load and Environment Monitoring												0.666						
Thermal Barrier Coating Health Monitoring																		
Bearing Health Monitoring			0.888															
Engine Emission Monitoring															0.888			
Structural Corrosion Monitoring				1														
Remaining Useful Life Quantification		0.666	0.777	0.666	0.777	0.777	0.666			0.666		0.666		0.666	0.888			
Digital Avionics Data Error Trending													0.777					
Enhanced Prognostics for Rotating Machinery															0.666			
Intermittency Analysis/Characterization		0.777								0.777	0.666							
Power Supply Performance Trending		0.777									0.888							
False Alarm Filtering	0.666	0.666								0.666	0.666		0.666					0.666
Composite Materials Damage and Failure Modeling					0.777													
Integrated Avionics Cross-Correlation Modeling													0.888					
Reconfigurable Power Systems		0.666									0.888							
PHM Design Standards and Education			0.666					0.666										

5 MAPPING OF DAMAGE CONDITIONS TO SHM REQUIREMENTS

In Section III, a list of high priority SHM technology requirements was summarized followed by documented damage conditions listed by the Adverse Events Table presented in the previous section. In this section, we provide an analysis performed to relate these two types of information. The objective of this analysis is to align future SHM requirements with documented damage conditions leading to aircraft safety incidents and accidents.

In conducting this analysis, experts have been asked to assess *whether a particular SHM technology requirement* (such as gas harsh environment sensor technologies, or intermittency analysis) *is relevant to potentially mitigating the effects of a particular damage condition* (such as turbine engine bearing faults, or wire chafing faults). For example, harsh environment sensors are highly relevant to the development of effective solutions for turbine engine bearing faults, but have less or no relevance to potentially addressing wire chafing faults, whereas intermittency analysis is high relevant to identifying and

The overall goal of the analysis is to *quantify this level of relevance* between documented technology requirements and damage conditions. In order to achieve this, an assessment has been made by each expert between all documented technology requirements (a total of 25) and all documented damage conditions (a total of 17) and the results are tabulated in Table 2 (columns – damage conditions, rows – SHM technology requirement areas). In order not to bias the results towards a particular damage condition, technology area, or SHM domain, this input has been solicited from experts with a wide range of SHM disciplinary backgrounds (airframe, avionics, propulsion, etc.).

The input in Table 2 is constructed such that a relevance relationship is assumed to be valid only if 2/3's or more of the experts solicited voted in favor of the existence of a particular relevance relationship. The remaining input (low or no relevance) is removed from the Table. Finally, the cells are normalized based on the overall input according to:

$$\mathrm{Re}\,l_i = \mathrm{Re}\,l_i / \mathrm{Re}\,l_{\max} \qquad (1)$$

Basically, if all experts voted in favor of the existence of a

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particular relevance relationship a relevance value 1.0 is assigned. This value changes between 1.0 (the maximum) and 0.666 (the threshold value used as the cut-off point for establishing relevance).

The results provide a common ground where each damage condition is mapped to one or more technology requirement area with varying degree of relevance. This paves the way for a formal analysis on the prioritization of SHM research requirements guided by potential impact on damage conditions, and thereby on aircraft safety. This prioritization analysis is explained next.

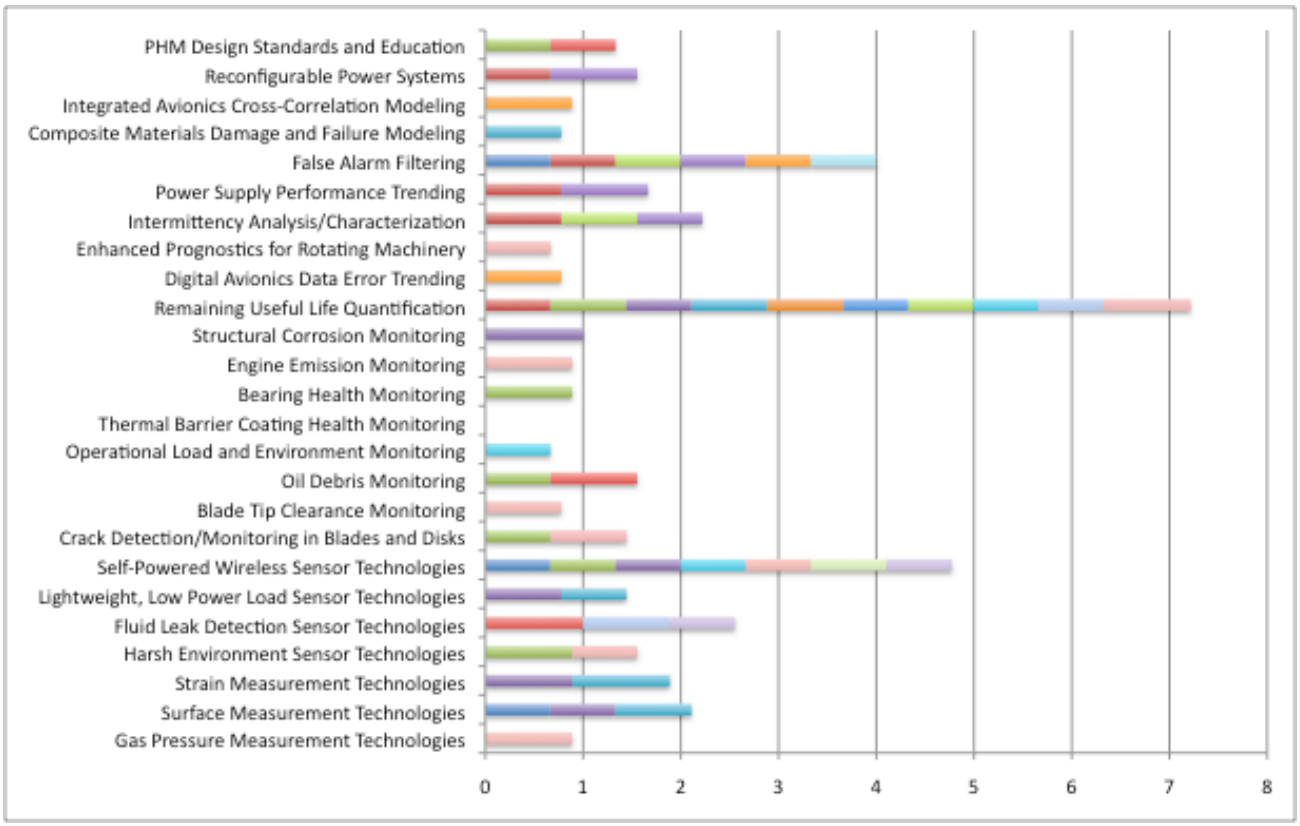

Figure 1. Prioritization of SHM Technology Requirements based on "Relevance" Mapping

6 PRIORITIZATION OF SHM REQUIREMENTS

Based on the mapping analysis explained in Section 5 and the documented accident and incident data, three different prioritization analyses are performed. These are explained next.

6.1 Prioritization Based on Relevance Mapping

In the first analysis, only the relevance mapping is taken into consideration. Accordingly, research requirements that can potentially impact the most of the damage conditions are identified. This is accomplished by summing the relevance values of a particular technology requirement area over all damage conditions (columns in Table 2). The results are summarized in Figure 1, where each element in the stacked bar plot represents the contribution of the relevancy of an individual damage condition. (For example, "gas pressure

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measurement technologies" are only relevant to "engine stall/faults in turbomachinery" with a degree of 0.888, whereas "false alarm filtering technologies" are relevant to six different damage conditions each with a degree of 0.666. The stacked bar shows the cumulative sum of these degree of relevancies.)

According to this analysis, top five SHM research requirement areas are (in descending order of priority):

1) Remaining Useful Life Quantification (7.215)

2) Self Powered Wireless Sensors (4.773)

3) False Alarm Filtering (3.996)

4) Fluid Leak Detection Sensor Technologies (2.554)

5) Intermittency Analysis and Characterization (2.220)

6.2 Prioritization Based on Accident Data

In the second analysis, both the relevance mapping and its potential impact on recorded accident data are taken into consideration. Accordingly, research requirements that can potentially impact the most number of accidents are identified (Figure 2). This is accomplished by assigning a potential "accident impact factor" for each technology according to:

$$\mathrm{Im}p_Accident_i = \sum_{j=1}^{\#\,of damage conditions} w_{ij} * num_accident_j \qquad (2)$$

where w_{ij}'s are normalized weights of the "relevance" values for each damage condition (in Table 2). The resulting "accident impact factor" provides an estimate of the number of accidents

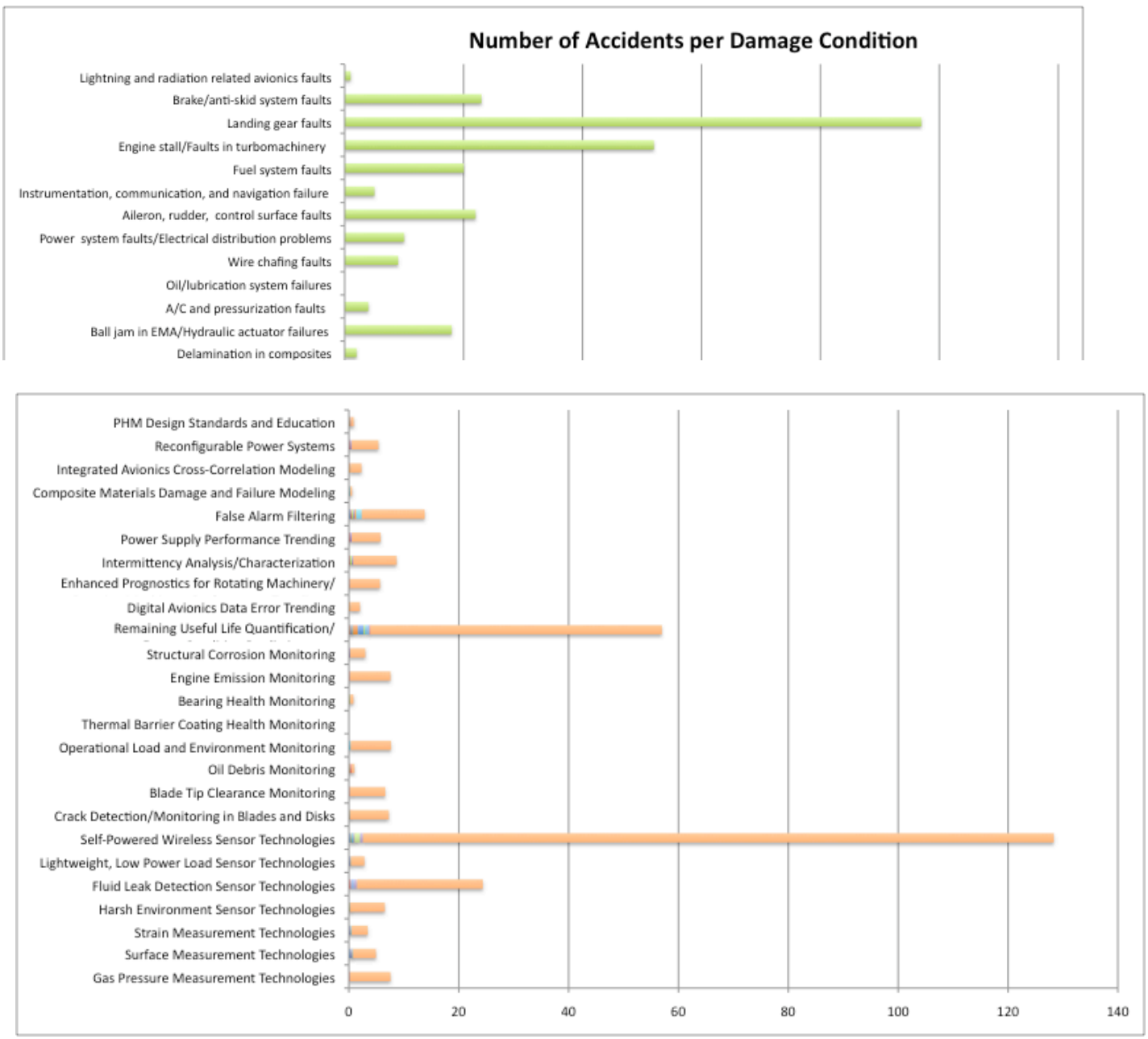

Figure 3. Prioritization of SHM Technology Requirements based on "Accident Data"

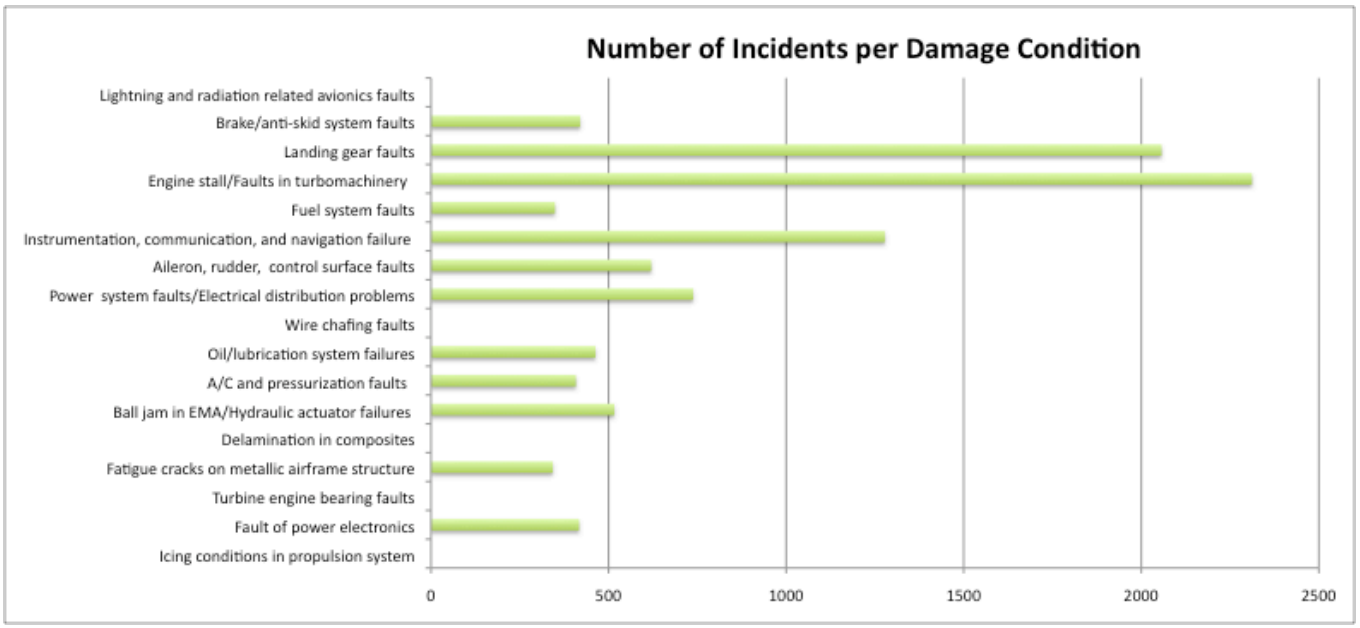

Figure 4. Number of Incidents per Damage Condition (as per Table 1)

a particular technology area can potentially mitigate. The results are summarized in Figure 3. (Basically this Figure shows the accident numbers for each damage condition distributed over relevant technology areas based on the normalized degree of relevancy. For example, the damage condition "icing conditions in propulsion systems" caused six accidents and is relevant to three technology areas with degree of relevancies of 0.666. Thus, each of these three technologies is assigned an accident impact factor of two for this particular damage condition. The stacked bar shows the cumulative sum of these accident impact factors.)

According to this analysis, top five SHM research requirement areas are (in descending order of priority):

1) Self Powered Wireless Sensors (125.772)

2) Remaining Useful Life Quantification (53.079)

3) Fluid Leak Detection Sensor Technologies (22.929)

4) False Alarm Filtering (11.476)

5) Intermittency Analysis and Quantification (7.865)

6.3 Prioritization Based on Incident Data

In the third analysis, both the relevance mapping and its potential impact on recorded incident data are taken into consideration (Figure 4). Accordingly, research requirements that can potentially impact the most number of incidents are identified. This is accomplished by assigning a potential "incident impact factor" for each technology area according to:

$$\mathrm{Im}p_Incident_i = \sum_{j=1}^{\#\,of\,adverse\,events} w_{ij} * num_incident_j \qquad (3)$$

where w_{ij}'s are normalized weights of the "relevance" values for each damage condition (Table 2). The resulting "incident impact factor" provides an estimate of the number of incidents a particular technology area can potentially mitigate. The results are summarized in Figure 5. (Basically this Figure shows the incident numbers for each damage condition distributed over relevant technology areas based on the normalized degree of relevancy. For example, the damage condition "fault of power electronics" caused 417 incidents and is relevant to five technology areas with different degrees of relevancy. Thus, each of these five technologies is assigned an incident impact factor proportional to their degree of relevancy for this particular damage condition. The stacked bar shows the cumulative sum of these incident impact factors.)

According to this analysis, top five SHM research requirement areas are (in descending order of priority):

1) Remaining Useful Life Quantification (2822.526)

2) Self Powered Wireless Sensors (2109.124)

3) Integrated Avionics Cross-Correlation Modeling (1222.095)

4) Digital Avionics Data Error Trending (1069.333)

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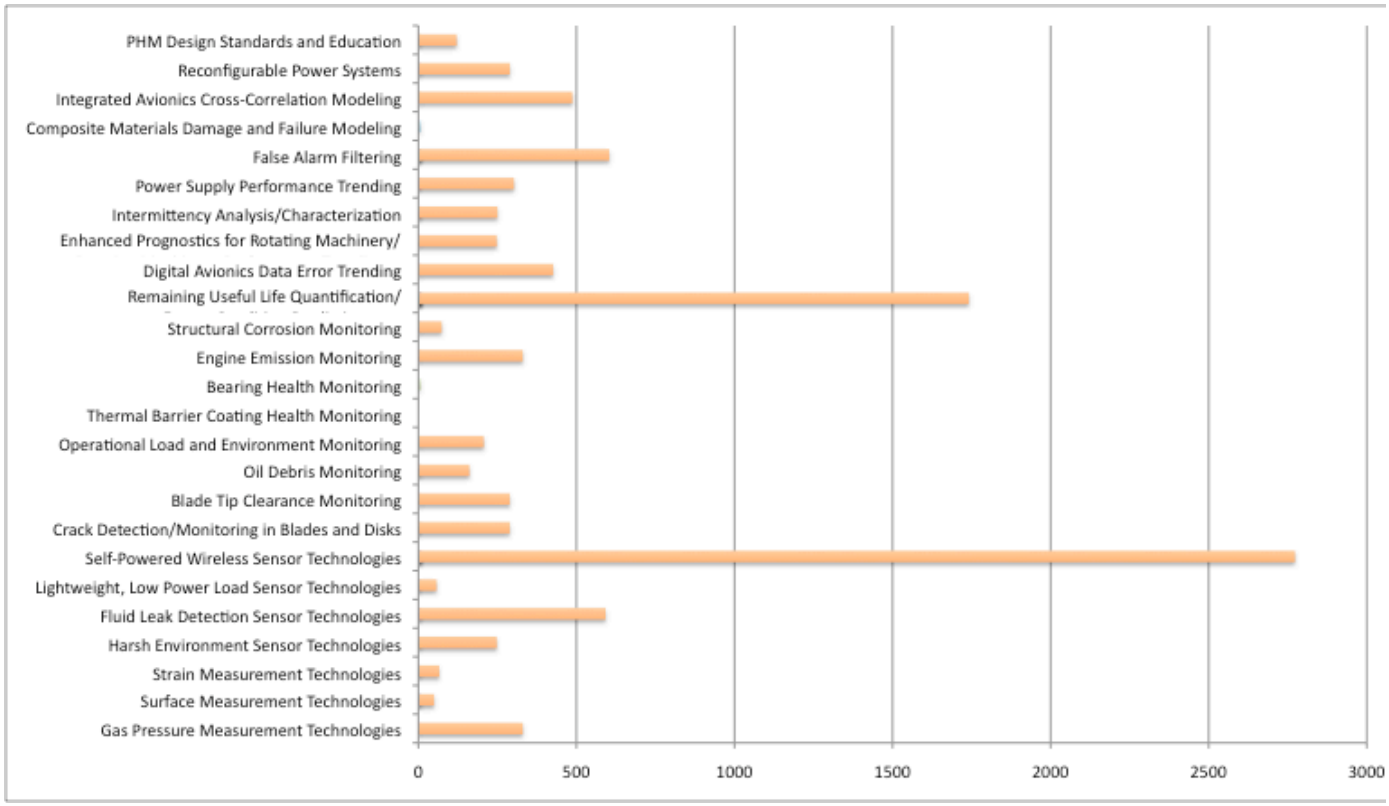

Figure 5. Prioritization of SHM Technology Requirements based on "Incident Data"

5) False Alarm Filtering (1054.973)

7 DISCUSSION AND CONCLUSIONS

This paper presented a study on the assessment of future requirements for SHM technologies and related research areas, and the results of a casual factor analysis based upon a systematic study of aircraft accident and incident data. The main focus of the paper is the mapping between SHM technologies and causal factors developed with the goal of prioritizing future SHM requirements in order to provide recommendations to support the development of system health management capabilities that will address safety related challenges facing current and future aircraft systems.

Accordingly, three prioritization analyses are run based on the assessed mapping between SHM research requirements and potential damage conditions as well as documented cases of aircraft safety incidents and accidents.

There are also several assumptions that the presented study is based upon. These assumptions pose certain limitations that are left to be addressed in the future research. For example, the severity of accidents and incidents are not taken into consideration. As presented in Table 1, some damage conditions cause accidents, which have greater fatality rates (depicted in column four), thus making them far more important. Secondly, the current implementation does not account for the challenges, risks, and costs associated with developing technologies in a specific technology area. Instead, the proposed "relevance" relationship is assumed to be sufficient enough for potentially mitigating accidents and incidents resulting from a particular damage condition. In the future, we plan to investigate costs, development and implementation risks, and financial and technical feasibility of each technology area and incorporate the results into a cost-benefit like framework for better assessment and prioritization of SHM technologies.

As a result of this study, we have found that certain health management technology areas hold the promise of improving aviation safety margins by mitigating potential adverse effects of the documented damage conditions. Based on the current study, we recommend the following SHM technology areas to be prioritized for future SHM technology development roadmaps:

1) Remaining Useful Life Quantification
2) Self Powered Wireless Sensors

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3) False Alarm Filtering
4) Fluid Leak Detection Sensor Technologies
5) Intermittency Analysis and Characterization
6) Integrated Avionics Cross-Correlation Modeling
7) Digital Avionics Data Error Trending

It is our hope that this study of SHM research requirements as well as the mapping of SHM technology areas to causal factors can provide a starting point for developing more effective technology development roadmaps and can further the widespread adoption of health management technologies within aeronautics.

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