# A Concept of Operations For An Integrated Vehicle Health Assurance System

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## Acknowledgments

*Level of Review*: This material has been technically reviewed by technical management.

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## Executive Summary

This document describes a Concept of Operations (ConOps) for an Integrated Vehicle Health Assurance System. This ConOps is associated with the Maintain Vehicle Safety (MVS) between Major Inspections Technical Challenge in the Vehicle Systems Safety Technologies (VSST) Project within NASA's Aviation Safety Program. In particular, this document seeks to describe an integrated system concept for vehicle health assurance that fully–integrates ground-based inspection and repair information with in-flight measurement data for airframe, propulsion, and avionics subsystems. The MVS Technical Challenge intends to maintain vehicle safety between major inspections by developing and demonstrating new integrated health management and failure prevention technologies to assure the integrity of vehicle systems between major inspection intervals and maintain vehicle state awareness during flight.

In order to effectively advance and implement improved vehicle safety, as well as provide a vision for achieving the safety of a single vehicle, a broader understanding of how to advance and maintain vehicle safety as whole is necessary. That is, in order to target both near and long term technology development, an understanding of what is necessary to produce an Integrated Vehicle Health Assurance is needed. The purpose of this ConOps is to discuss a vision of how

such Integrated Vehicle Health Assurance can be achieved. Integrated Vehicle Health Assurance is broader than a conventional vehicle health monitoring system. Rather, it is a system level approach focused on assuring overall vehicle health from the design stage until retirement of the vehicle. It combines design elements, enhanced manual inspection techniques (on-ground), in-flight material mitigation techniques, and an advanced integrated health management system.

This Integrated Vehicle Health Assurance Concept is derived in the context of historical factors, present operational standards, and a projection of future safety hazards. In order to understand this context, this document will:

- Review factors influencing aviation safety, both at the vehicle and subsystem levels. This will rely on extensive previously completed system and safety studies in the field.

- Review the present state-of-the-art (SOA) of Vehicle Health Assurance related to the vehicle, as well as the airframe, avionics, and propulsion subsystems.

- Describe NASA contributions to the SOA of Vehicle Health Assurance, as well as NASA's capabilities to advance the SOA especially in the airframe, avionics, and propulsion subsystems.

- Review of other agencies assessments of technology development needed for Integrated Vehicle Health Assurance.

Based on this overview, a proposed Integrated Vehicle Health Assurance System (IVHAS) is presented. This IVHAS encompasses the fields of Integrated Vehicle Health Management (IVHM), vehicle sustainment (scheduling and performing inspection, repair and overhaul actions), and design for safety. It is a system level approach focused on assuring overall vehicle health.

The approach of this ConOps takes into account that NASA does not build vehicle systems. NASA's role in the Aviation Safety Program is to provide a wide range of tools to enable those who do build, operate, and maintain aircraft to be able to achieve the next generation of vehicles with properties that enhance the nation's and public's safety. These tools must be practical to allow fleet wide implementation and potentially enable other benefits such as decreased emissions, increased performance, and decreased operating costs. Major impact on the available approaches and tools related to aviation safety within the next 5 years is a major goal, but doing so in such a way as to establish the foundation for paradigm shifts in aviation technology.

A core aspect of this ConOps approach is that in order to achieve a safer vehicle and maintain aviation safety in the future, more intelligent vehicle systems are necessary. Local processing and hierarchal approaches are needed with an emphasis on producing intelligent vehicle systems. The fundamental concept for an IVHAS is that increased intelligence of the vehicle will enable improved safety. This increased intelligence is established from the bottom up with integrated smart sensors and materials coupled with diagnostics and prognostics operating locally, feeding

into smart nodes and subsystems, and finally across the vehicle. The envisioned intelligent system is enabled by integrated, local smart detection, diagnostics, and prognostics.

A safer vehicle is one that is constructed with materials that avoid safety issues, evaluates its own health and mitigates its own problems where appropriate, and provides information to flight and ground personnel in a simple, actionable way. Not all problems can be addressed given the resources of the MVS Technical Challenge. Rather, a range of tools will be targeted based on safety impact, and available NASA capabilities.

This IVHAS will concentrate on the subsystem concepts, but will also describe the framework of how an IVHAS spanning the whole vehicle and ground operations could be established for future development. This framework motivates and guides the development and testing of technology for MVS. Foundational technologies for the next 5 years to enable IVHAS include:

- Innovative sensors and diagnostic tools to provide information for the incipient diagnosis and prevention of potential critical failures

- High temperature engine sensor systems that directly monitor compressors and turbines for reliable engine health monitoring

- Airframe and engine materials and coatings that detect damage and minimize premature failures from fatigue, fracture, impact, and corrosion

In particular, the MVS Technical Challenge proposes a three-prong solution to maintaining safety between inspections. First, technologies will be developed to enhance existing inspection methods to identify damage in areas that are difficult to access. Second, advanced materials and coatings will be developed to prevent damage initiation and growth. Finally, automated large area assessment, coupled with on-board health monitoring, will identify damage or faults that may occur after an inspection.

The goal of the MVS Technical Challenge is to maintain vehicle safety between these major inspections. The approach toward meeting this goal is through *preventative* methods using advanced materials and material coatings to prevent damage from initiating or progressing, and through *mitigation* approaches providing better inspection methods to detect damage in inaccessible areas, and on-board monitoring of faults and failures. By providing multiple opportunities to prevent or identify unsafe vehicle health states, current levels of safety can be maintained or exceeded even as air travel demand, vehicle complexity, and the use of new materials increases.

*The MVS Technical Challenge will not develop a complete Integrated Vehicle Health Assurance System in the next 5 years.* Instead, the concentration will be on subsystem technology development with activities in Sensor and Diagnostic Tools, High Temperature Engine Sensor Systems, and Materials and Coatings. Sensor and Diagnostic Tools affect the airframe, avionics, and propulsion systems including work in Digital Assessment of Aircraft Structural Health, Propulsion System Diagnostics, and Wiring Fault Diagnostics. High temperature engine sensor

systems provide a range of harsh environment sensor and sensor system technologies for improved monitoring of the engine with, for example, High Temperature Smart Sensor systems. The Materials and Coatings element affects the airframe and propulsion subsystem including work in Integrated Sensing and Healing Systems, Bonded Joints and Repairs, and Engine Emerging Discs and Composite Materials Health.

The approach provided by this ConOps is intended to help optimize technology selection and development, as well as allow the initial integration and demonstration of these subsystem technologies over the 5 year span of the VSST program, and serve as a guideline for developing IVHAS technologies under the Aviation Safety Program within the next 5 to 15 years. Examples of how such an IVHAS system can be implemented and its affects on safety will be discussed related to three different scenarios of in-flight hazards after a major inspection. These examples are intended to demonstrate a full vehicle approach spanning design, flight, and maintenance that is based on the concept that a smarter vehicle is a safer vehicle. A long-term vision of IVHAS (beyond the scope of this program) is provided to describe a basic roadmap for more intelligent and autonomous vehicle systems. The tools that the MVS Technical Challenge will provide and the technology direction set by this ConOps are intended to be a foundation and a vision for improved vehicle safety in the future.

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# 1.0    Overview and Scope

## 1.1    Purpose

This document describes a Concept of Operations (ConOps) for an Integrated Vehicle Health Assurance System (IVHAS). This ConOps is associated with the Technical Challenge to Maintain Vehicle Safety (MVS) between Major Inspections in the Vehicle Systems Safety Technologies (VSST) Project within NASA's Aviation Safety Program. In particular, this document seeks to define an integrated system concept for vehicle health assurance that fully integrates ground-based inspection and repair information with in-flight measurement data for airframe, propulsion, and avionics subsystems.

## 1.2    Programmatic Relevance

This Concept of Operations (ConOps) for an Integrated Vehicle Health Assurance System is being developed within the MVS Technical Challenge. This Technical Challenge intends to maintain vehicle safety between major inspections by developing and demonstrating new integrated health management and failure prevention technologies to assure the integrity of vehicle systems between major inspection intervals and to maintain vehicle state awareness during flight. Between the fiscal years (FY) of 2012 and 2016, this Technical Challenge will develop and demonstrate health management concepts for the airframe, propulsion, and avionics subsystems. The technology focus areas are:

- Sensors and Diagnostic Tools: Innovative sensors and diagnostic tools for the incipient diagnosis and prevention of potential critical failures

- High Temperature Engine Sensor Systems: High temperature engine sensor systems that directly monitor compressors and turbines for reliable engine health monitoring

- Airframe/Engine Materials: Airframe and engine materials and coatings that detect damage and minimize premature failures from fatigue, fracture, impact, and corrosion

Thus, Integrated Vehicle Health Assurance is broader than a conventional vehicle health monitoring system. Rather, it is a system level approach focused on assuring overall vehicle health. It combines design elements, enhanced manual inspection techniques (on-ground), in-flight material mitigation techniques, and an advanced integrated health management system.

*The MVS technical challenge will not develop a complete IVHAS in the next 5 years*. Instead, the concentration will be on subsystem technology development. However, the design concept of such a complete system to assure vehicle health will serve to help optimize technology selection and development, as well as help enable the potential initial integration of these subsystem technologies as appropriate over the 5 year span of the VSST Project. Further, key research work towards the development of such a complete system can be considered in the next 5 years in MVS.

Additionally, the MVS activities are aimed to directly affect the other two VSST Technology Challenges: Improve Crew Decision-Making and Response in Complex Situations, and Assure Safe and Effective Aircraft Control under Hazardous Conditions. The ConOps document also provides a framework as to how vehicle health assurance technologies can improve crew decision making and assure effective aircraft control.

## 1.3 Approach

Aircraft vehicle health assurance encompasses the fields of Integrated Vehicle Health Management (IVHM), vehicle sustainment (scheduling and performing inspection, repair and overhaul actions), and design for safety. These are broad areas of investigation, the topic of a vast array of publications and peer-reviewed literature, and often needs to be addressed towards specific application environments. IVHM standardly includes the ability to monitor as well as provide management of the health state of the system in-flight, but typically is not integrated into the design phase. Often these approaches concentrate on ground systems or flight systems, but interaction between flight and ground systems is presently limited. Vehicle health assurance technologies provide a variety of benefits including improved aircraft safety and reliability, reduced maintenance time and cost, and reduced unscheduled maintenance actions. This document describes an approach toward an IVHAS.

The IVHAS provides a framework that improves vehicle safety by, in part, combining ground and flight information, and this document describes the required technology developments relevant to meeting the MVS Technical Challenge. A broad rationale is also provided for the basic structure and framework of a vehicle-wide IVHAS, as well as the technology components necessary for such a system. The approach used to achieve this ConOps for IVHAS is:

- Review factors influencing aviation safety, both at the vehicle and subsystem levels. This will rely on extensive previously completed system and safety studies.

- Review the present state-of-the-art (SOA) of Vehicle Health Assurance related to the vehicle, as well as the airframe, avionics, and propulsion subsystems.

- Describe NASA's contributions to the SOA of Vehicle Health Assurance, as well as NASA's capabilities to advance the SOA, especially in the airframe, avionics, and propulsion subsystems.

- Present a proposed Vehicle Health Assurance Concept. This will concentrate on the subsystems, but will also describe how the framework of an IVHAS that spans the whole vehicle and ground operations could be established.

- Discuss how such a system would be implemented, a long-term vision, and the possible benefits.

- Provide three relevant examples of how this Vehicle Health Assurance Concept can improve the safety of the vehicle in response to hazards occurring between major inspections.

While this document will present an overview of the broader field of health assurance and management, it is not meant to provide an all-inclusive review of the entire vehicle health management field. In general, each of the sections are generally meant to be self-contained, although necessarily need to feed into the document as a whole. Furthermore, the goal is not a full technically detailed specification of an Integrated Vehicle Health Assurance System. The primary goal is to present a concept of operations intended to guide the development and integration of VSST funded subsystem technologies. Additional factors, such as IVHAS economic benefits, fleet-wide safety assurance, and military dual-use applicability are discussed because they are important considerations for our partners that help to ensure adaptation of the technology described in this report. But the primary focus of this ConOps is on maintaining vehicle safety in commercial aviation.

## 2.0    Introduction

## 2.1    Brief Overview of Vehicle Systems Safety Technologies (VSST) Program

Public benefits derived from continued growth in the transport of passengers and cargo are dependent on the improvement of the intrinsic safety attributes of current and future air vehicles. The Aviation Safety Program (AvSP) is addressing this challenge by conducting cutting-edge fundamental research that will yield innovative algorithms, tools, concepts, and technologies from the discipline level up to the subsystem and system level. As a part of the AvSP Program, the Vehicle Systems Safety Technologies (VSST) Project is primarily focused on improving individual vehicle safety by addressing three Technical Challenges (TC's): 1) Improve Crew Decision-Making and Response in Complex Situations (CDM); 2) Maintain Vehicle Safety between Major Inspections (MVS); and 3) Assure Safe and Effective Aircraft Control under Hazardous Conditions (ASC). These three technical challenges are represented in Figure 2.1. The overall goal of the VSST project is to develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, systems, and operating concepts. All three TC's contribute to this goal. Each addresses an important contributor to accidents and also considers the emerging trends toward future causal factors with an emphasis on single vehicle safety, not fleet wide issues.

CDM provides flight deck capabilities that enable pilots to make more informed decisions when confronted with complex situations. From a review of recent accidents, pilots are increasingly faced with complex, multi-faceted situations that can't entirely be handled by referring to a checklist. Given the complexities of current-day operations and trends toward greater levels of automation and information availability, future systems should be considered that can help pilots assess these situations and execute an informed course of action. CDM has focused its work on low altitude (near airport) and surface operations because those domains often cause the highest workload and historically have the highest accident rates.

ASC research seeks to assure flight safety under hazardous conditions by characterizing and mitigating the impacts of hazards on vehicle dynamics and control. Hazardous conditions being addressed by ASC include adverse onboard conditions resulting from vehicle impairment or inappropriate crew response, external disturbances, and abnormal flight conditions (vehicle upsets). ASC research will provide pilots with predictive information on impending loss of control, while also informing about changes to the safe maneuvering envelope of the aircraft. Moreover, ASC research emphasizes a synergistic pilot/automation response to aircraft control under hazardous conditions. This approach helps ensure that pilots and their control systems are working together and not making the problem worse.

Improve Vehicle Safety by Proactively
Mitigating Current and Future Risks
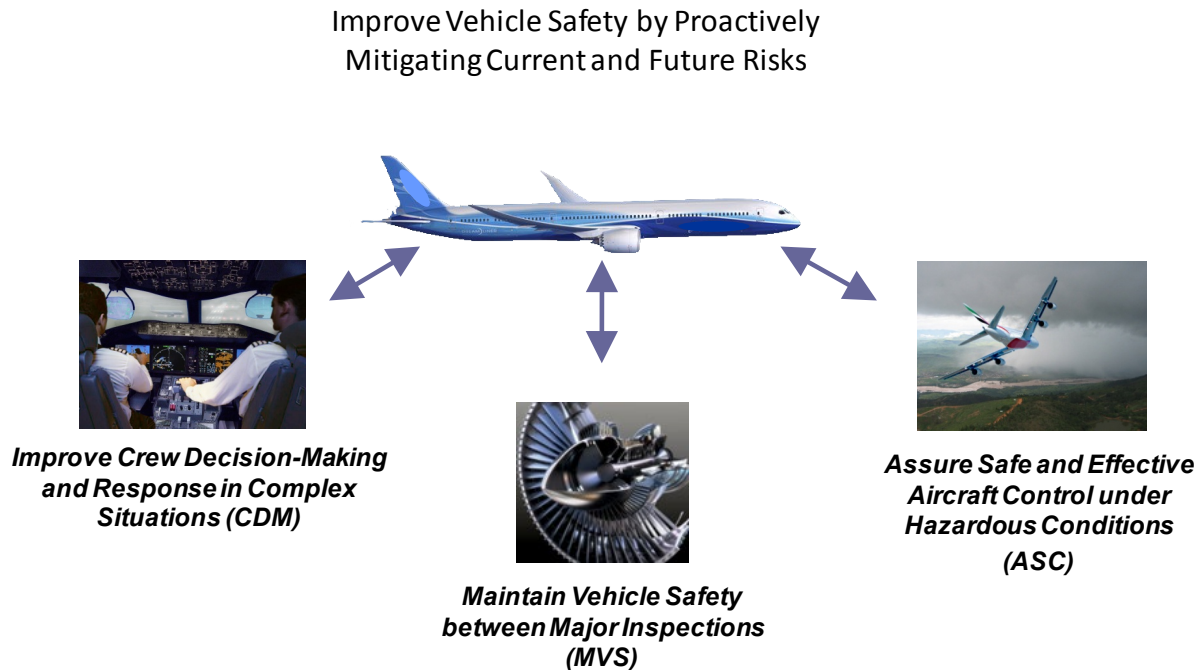


Figure 2.1.—An organizational schematic of the VSST Project.

## 2.2 Brief Overview of Maintaining Vehicle Safety (MVS)

MVS addresses critical risks for maintaining vehicle safety between major inspections. The goal of the MVS Technical Challenge is to develop and demonstrate new integrated health management and failure prevention technologies to assure the integrity of vehicle systems between major inspection intervals and maintain vehicle state awareness during flight. Currently, much of the information about an airplane's health is obtained during a major inspection. These inspections are thorough, costly, and are done at set intervals based on fleet-wide averages for system and component reliability. There is a generous safety margin built into these intervals, but there are occasions where problems can come up during operations that were undetected at the last major inspection. Unique failures can happen due to the service history of individual vehicles. Contributing factors include the following: engineering predictions determined at the beginning of aircraft service that do not take into account vehicle history; inspections based on vehicle life assessments and fleet-wide schedules and not vehicle condition; faults and failures are detected utilizing external inspections which are not always effective; and information obtained during an inspection may not be properly acted upon in order to prevent a hazardous situation. Examples include of cracking in a wing rib discovered during other unscheduled maintenance activities [1], and continued use of a known faulty accelerometer which, when coupled with other system faults, caused a malfunction of the autopilot system [2]. The ability to detect these failures after major inspections, or due to events that happen in flight, is presently limited.

MVS works to provide information on potential safety-related systems problems to support in-flight decision making and targeted maintenance that can address those problems. It accomplishes this goal through integrated systems consisting of advanced sensors as well as

diagnostic and prognostics algorithms. It also develops capabilities to help preclude some of the most critical failures that can arise.

Together, MVS with the other VSST TCs address important factors in the accident chain. NASA, working in collaboration with external partners, plans to deliver capabilities that address each of these TCs. This will build upon prior successes and make important contributions to aviation safety. This is illustrated in Figure 2.2, which shows the relationship between the various components of MVS, overall vehicle level health assessment, and the use of these technologies to improve crew decision-making, assure safe control, and target maintenance between inspections.
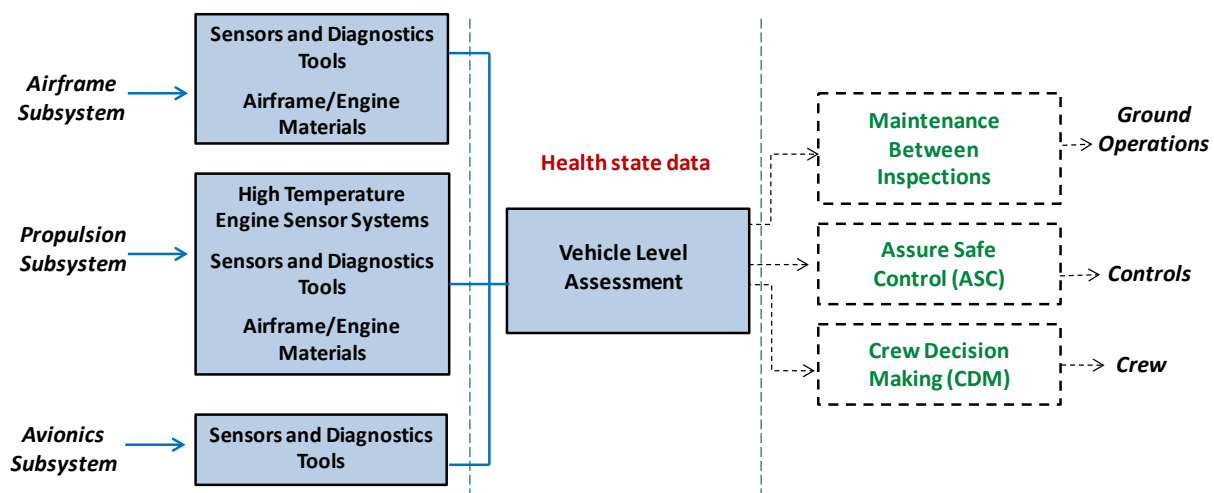


Figure 2.2.—A schematic of the MVS approach and its general relationship to Vehicle Level Assessment, Ground Operations, Controls, and Crew Decision-Making

The MVS technologies are not intended to directly provide information to the crew or affect the control system. However, they do provide information to the Technical Challenge Problems that are associated with Improving Crew Decision-Making and Response in Complex Situations, and Assuring Safe and Effective Aircraft Control under Hazardous Conditions. These Technical Challenges are involved in determining the proper information to provide to the crew, and how to maintain aircraft control in unforeseen conditions. It is through such interfaces that decisions are made with respect to how to handle the information provided from MVS, and thus what information is to be provided to the crew, or potential actions by the flight control system if any. MVS will also provide information for later analysis and use by, for example, the ground maintenance crew.

## 3.0    Factors Influencing Aviation Safety

### 3.1    Vehicle Level Safety Factors

There are a range of factors that influence aviation safety. In effect, safe flight of the vehicle is achieved through the confluence of interacting factors including the crew, the vehicle, environmental factors, and the supporting aviation infrastructure. The Civil Aviation Authority (CAA) [3] identified 283 worldwide fatal accidents during the 10-year period from 1997 through 2006, resulting in a total of 8,599 fatalities to passengers and crew members. Of these 283 accidents, 254 of them had identifiable primary and contributing causal factors. The most likely causal factor group is the "Flight Crew."

The second most likely contributor to fatal accidents is in the "Aircraft Related" category, with 42% of all fatal accidents involving at least one aircraft-related causal factor as shown in Figure 3.1. (Note that each accident can have more than one factor and that these are not mutually exclusive.) Within the "Aircraft Related" category, the most common causal factor group is "Engine," with 17% of all fatal accidents citing "Engine failure or malfunction" as a causal factor. The next most likely aircraft-related causal factor groups are "Aircraft Performance/Control" and "Aircraft Systems." The remaining two aircraft-related causal groups, "Aircraft Structure" and "Aircraft Design," are of significant importance to airframe research. Causal factors in these groups are "Corrosion or fatigue," "Overload failure," "Design shortcomings," and "Manufacturing defects."
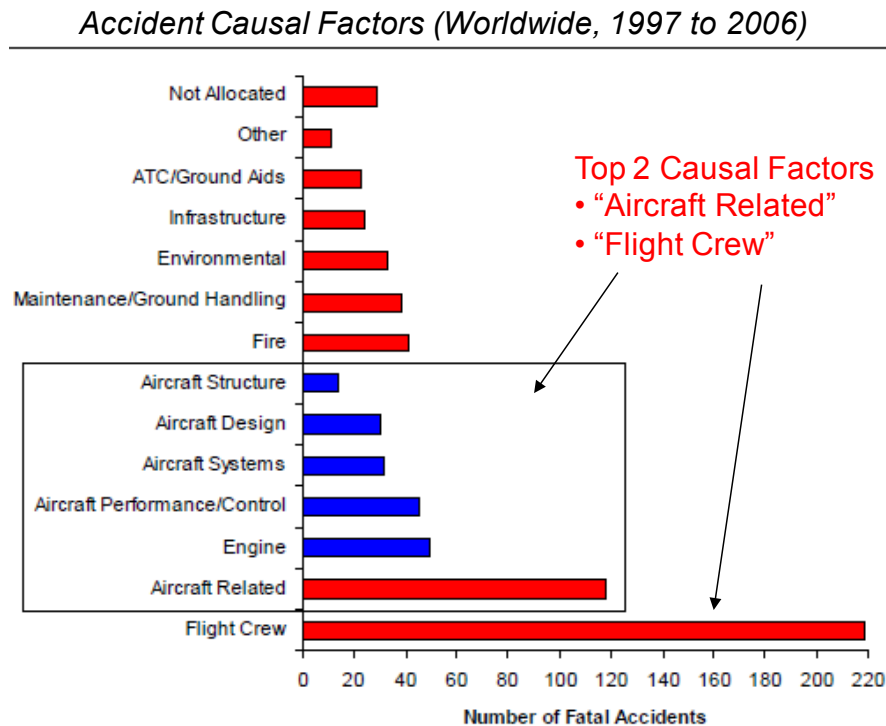


Figure 3.1.—Most likely causal factor groups for all fatal accidents from 1997 to 2006 [3]. (Note: causal factors included in "Aircraft Related" category shown in blue.)

Although fatal accidents are discussed above, aviation safety is also influenced by more frequent safety incidents and accidents that affect the safety of the passengers and crew, but do not necessarily lead to a fatality. For example, an incident could include an in-flight engine shutdown, but not result in a fatal accident. These incidents affect aviation safety, and could under some conditions, when combined with other factors, lead to more serious accidents or fatalities. A statistical analysis of 1997-2006 NTSB (National Transportation Safety Board) accident and Federal Aviation Administration (FAA) incident data identified the top "tall poles" based on four types of Federal Aviation Regulations (FAR) operations (Part 121, Part 135-Scheduled, Part 135-Non-Scheduled and Part 91) and categorized using the CAST/ICAO (Commercial Aircraft Safety Team/International Civil Aviation Organization) Common Taxonomy [4]. In common to the FAR operations and identified as among the top "tall poles" were "System Component Failure—Powerplant", "System Component Failure—Non Powerplant", and "Loss of Control—In Flight" as major factors in accidents. The "System Component Failure—Powerplant" (SCF Powerplant) refers to component failures related to the engine while "System Component Failure—Non Powerplant" (SCF Non Powerplant) refers to component failures of other aircraft components. Overall, there are far more incidents and accidents than fatal accidents, but the general pattern of the incidents and accidents also support the importance of airframe, propulsion, and avionics systems in maintaining aviation safety. Each of these subsystems have different types of component failure mechanisms. However, there is often interdependence between the operation and safety of the different subsystems that affect each other and the overall safety of the vehicle.

Next generation vehicles are likely to have increased usage of advanced, lightweight materials and structures, which will potentially introduce new safety challenges. As an example, the use of composite materials for fuselage structures on next-generation vehicles has increased significantly over the past 40 years. The Boeing 787 and Airbus A350 XWB (extra wide body) have a 50% composite structure by weight, compared to the current generation Boeing 777 that has 10% composite materials. The fuselage structure of the Boeing 787 is made mostly of composite materials, even though these materials exhibit complex failure modes that require new inspection and repair methods to ensure comparable safety to traditional metallic airframe materials.

The aircraft safety statistics to date give an indication of past safety issues. These areas will continue to be a challenge. However, in the future, new safety problems may come into play for three major reasons: 1) Increasing air traffic means that if the safety rate remains the same, the number of accidents will increase, while at the same time the existing fleets will continue to age generating new potential safety hazards. 2) It is desired that new materials and capabilities be incorporated in future aircraft to improve fuel efficiency and reduce noise and emissions while safety is maintained at existing levels. 3) Operation of the vehicle system beyond standard design limits or expected lifetimes. System-level effects of the integration of new flight technologies are unclear and subsystem dependent. Overall, in order to understand the ability to provide health assurance across the vehicle, the ability to understand safety issues in each subsystem is necessary. The next sections review safety issues for the subsystems airframe, avionics and propulsion.

Currently, vehicle health assurance in commercial aircraft is limited in *scope* (health monitoring and health management is still evolving), level of *maturity* (schedule-based or reactive maintenance is commonplace, while autonomous healing is in its infancy), and *integration* (most health assessment approaches target individual components rather than assessing health at the subsystem or vehicle level). Significant amounts of information regarding necessary repairs and the susceptibility of current design methods to damage and degradation only become available after tear-down for ground inspection. Additionally, design tools for advanced materials and next generation aircraft are still emerging technologies.

## 3.2    Airframe Safety Factors

A 2011 Aeronautics Research Mission Directorate (ARMD) funded study by the RAND Corporation "Advancing Aeronautics: A Decision Framework for Selecting Research Agendas" stated the following as an illustrative Aeronautics Grand Challenge in safety: "Maintain passenger safety levels as the industry moves from aluminum to composite airplanes" [5]. The rapidly expanding use of composites in primary aircraft structures may present new safety challenges to maintain the present safety levels due to complexity of the material systems and failure modes, potential variability in strength properties, and lack of experience in composites in commercial operations, inspection and repair. This is coupled with maintaining the safety of conventional metal-based airframe systems as notable airframe safety challenges. This section describes factors influencing the safety of the airframe both historically and taking into account emerging factors.

### 3.2.1    Airframe Historical Data

The airframe structure spans the vast majority of the vehicle and has historically been composed of metallic skin and stiffener structures. Tiffany et al. [6] documents historical threats to aircraft structure and strategies that have been established, in some cases after years of operational experience and accidents, to mitigate these threats. A range of serious threats to structural safety were identified and are summarized in Table 3.1. Each of these threats can then produce its own typical failure mechanism with fatigue and abrupt cracking being the most prominent. Figure 3.2 gives a United States Air Force (USAF) example for 37 non-combat aircraft losses attributed to structural failure [6,7]. The majority of these losses are attributed to fatigue, debonding of the structure, maintenance, or a combination of these issues.

Fatigue failures are challenging to predict primarily due to the large number of variables that can affect the times to develop critical crack sizes in the operational environment. Unanticipated conditions (e.g., debonding from a stiffener) can lead to excessive local loads and stresses beyond the standard design limits. Additionally, as the lives of aircraft are extended, complex corrosion fatigue issues are more likely to occur. Such conditions can lead to structural degradation and potential safety hazards. Abrupt cracking failures, caused by penetration due to impacts, ballistic damage or explosions, are threats that are largely addressed by developing structural redundancies and fail-safe concepts into the airframe. While most structural engineers believe that the problems associated with high operational loads have been solved, accidents/incidents continue to be observed as a result of unusually high operational loads caused by pilot error or faulty flight control systems. Accidents have in the past been averted by a 1.5

factor of safety used to establish ultimate design loads. However, unanticipated conditions can result in excessive loads and operation beyond standard limits. Such conditions can lead to structural degradation and potential safety hazards.

TABLE 3.1.—A LISTING OF STRUCTURAL THREATS
AND THEIR ASSOCIATED MECHANISMS OF FAILURE [6].

| Threat | Mechanism of Failure |
|---|---|
| High Local Stresses | Fatigue |
| Manufacturing/Material Defects | Fatigue |
| Maintenance Damage/Deficiencies | Fatigue |
| Environmental Damage | Corrosion (material loss) |
| Impact from Ground Equipment | Fatigue |
| Impact due to Uncontained Engine Failures | Abrupt Cracking |
| Impact due to Bird Strikes | Abrupt Cracking |
| Impact due to Runway Debris | Abrupt Cracking |
| Explosive/Ballistic Penetrations | Abrupt Cracking |
| High Operational Loads | Overload |
| Widespread Fatigue Damage | Fatigue |
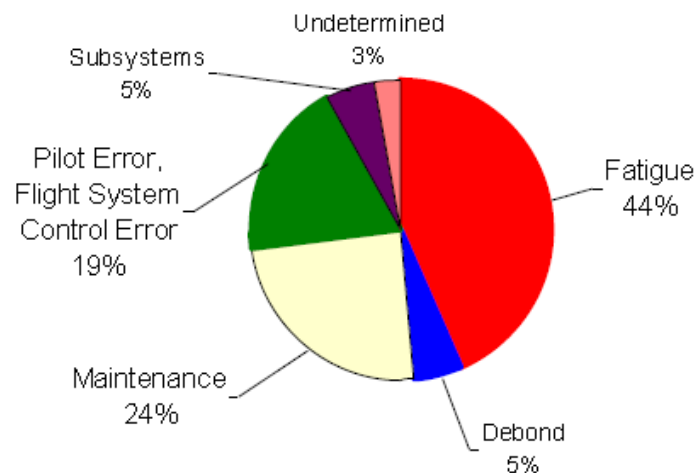


Figure 3.2.—Percentages associated with types of causes associated with 37 United States Air Force Structural Failures [6,7].

In general terms, structural components are found to be adequately robust, over their service life, by a series of structural design requirements that must be satisfied at specified load levels. Consequently, it is critical to know the loads that are applied to the structure. The design process begins with identification of the structural loading spectrum that the assembly, part, or surface will be expected to experience while in service. This includes the identification of the most severe, but nonetheless, expected loading conditions. Often, accidents involve the realization that either the actual loading conditions are more severe than expected, or the capability of the component, structure, or system is less than expected due to some unanticipated condition being present [8]. These unanticipated conditions have regularly occurred in metallic aircraft, as

evidenced by the recent discovery of cracking in a wing rib on several Airbus A380 aircraft due to design and manufacturing defects [1]. This fleet-wide problem was discovered during unscheduled maintenance for an unrelated engine failure. The fact that these conditions continue to occur in metallic aircraft suggests the potential for an increased likelihood of unanticipated failures with the increased introduction of large integral metallic structures, such as the wing ribs for the A380 aircraft, and complex composite material systems for aircraft primary structure.

### 3.2.2    Airframe Emerging Factors

The Rand Corporation was tasked to independently assess NASA's ARMD portfolio as well as the current and future needs of the aviation community [5]. Highlighted in this report is the trend of using new engineering materials to reduce aircraft weight and subsequently improve efficiency. While the use of new materials can be beneficial, new challenges are introduced. Particularly, the increased use of composites for primary aircraft structure "…may have inherently different safety implications that will drive how we treat aging aircraft giving us the opportunity to weigh the benefits of composite structures against their weaknesses." [5]. Here, the challenge of maintaining current safety standards for commercial aircraft utilizing new materials and systems is emphasized. Similar concerns have been identified in a study from Boeing, where it is noted that safety is improved by minimizing uncertainties and risk, yet the introduction of new structural materials inherently increases uncertainty [9].

> Traditional metallic-based aircraft structures have a long history, but unanticipated conditions and extended operation can lead to structural degradation and potential safety hazards. The introduction of composite materials is a significant paradigm shift in the design of aircraft structures. Material characterization and measurement technologies must advance in parallel in order to assure the future safety of these airframe structures.

## 3.3    Avionics Safety Factors

### 3.3.1    Avionics Historical Data

The field of aviation electronics, or avionics, is incredibly broad and generally includes all sensors, communication and navigation equipment, along with the vast array other electrical systems needed to fulfill the various roles required by modern aircraft. While there are an equally great number of safety concerns regarding many of these individual systems, this document focuses on the safety critical subsystems relevant to *maintaining safety between major inspections*; and in particular where single point failures can lead to multiple system faults and/or directly lead to loss of communication, power, or control of the aircraft.

With these considerations in mind, our focus is on one critical, but sometimes overlooked, avionics subsystem with a substantial historical record relevant to both current and future aircraft: wiring.

### 3.3.1.1    Electrical Wiring and Interconnect System

The electrical wiring and interconnect system is a common point of failure for nearly all avionics equipment, and it received a great deal of attention in the late 1990s due to two tragic accidents: the July 1996 mid-air explosion of the Boeing 747 TWA Flight 800 and the crash of a Swissair MD-11 in Nova Scotia. The National Transportation Safety Board (NTSB) later determined the cause of the TWA 800 accident to have been a wiring failure that led to an ignition spark in the fuel tank [10]. It is believed electrical arcing originating from an in-flight entertainment cable caused the Swissair disaster [11]. These two tragic accidents generated nearly a decade of study to uncover the underlying issues that caused them, the results of which are briefly summarized below (with full details deferred to the references).

Although the TWA 800 and the Swissair tragedies are cited as the impetus to research and development efforts in addressing wiring in aircraft, there have been a considerable number of incidents that have not resulted in crashes but have been attributed to electrical wiring failures. Avionics Today [12] reported that during the cruise phase of a flight, a "smoke" event is more than twice as likely as an engine problem to cause an unscheduled landing, according to a study of service difficulty reports. In-flight electrical fires are also not rare events: According to Captain Jim Shaw, manager of the in-flight fire project for the United States Air Line Pilots Association (ALPA), there are on average three fire and smoke events in jet transport aircraft *each day* in USA and Canada alone, and the vast majority are electrical [13].

The Coast Guard, NAVAIR, NASA and the FAA all have programs (including joint programs) to assess the most prominent failures in electrical wiring. Although each agency has different aircraft, different maintenance practices, different data collection methods, and different operating environments, all of these agencies experience very similar wiring issues. A more extensive summary of these studies is presented in [14]. To take a particular example, Figure 3.3 shows the wiring issues identified after deconstructing six commercial aircraft (DC-8, DC-9, DC-10, 727, 737, 747), in a study conducted by the FAA [15]. More than half of all of the wiring faults found were related to a breach in the insulation, or chafing. Another 14% of these were cut or broken wires that may have arisen from chafing. Furthermore, in 2005 the FAA summarized [16] the 7 most common problems: burned, loose, damaged, shorted, failed, chafed, and broken wires account for 84% of all wiring failures. The above highlighted study overwhelmingly points to chafing as the common precursor to a large majority of severe wiring issues (opens, shorts, and arcing which lead to smoke and fire events). In addition to chafing, other studies have shown connector related faults are also frequently cited as a primary area of concern [14]. Ultimately, the studies summarized here led to the FAA issuing new rules in 2007 on wiring maintenance and inspection.
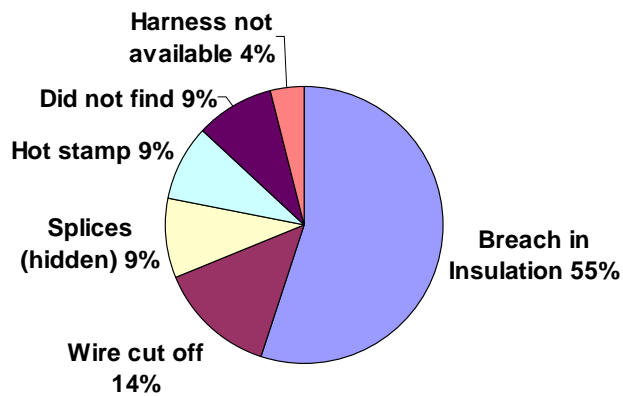
Figure 3.3.—FAA findings from examining 6 aircraft: DC-8, DC-9, DC-10, 727, 737, and a 747 [14].

Even with these new rules now in place, one still finds evidence of wiring system difficulties. A large source of current and publically available information lies in the Service Difficulty Reporting database [17] maintained by the FAA. In particular, a search for fault code 2497 (power system wiring) reveals 94 recorded incidents in 2011 alone, many of which, but not all, are in commercial aircraft. A search for fault code 2797 (flight control system wiring) reveals 45 records for the same year, including at least one chafing incident in a Boeing 737 that led to an emergency landing [Unique Control #CA110125022]. Thus, while there have been no major wiring related fatalities in part 121 operations (commercial aircraft) in the United States since the TWA and Swissair accidents at the end of the 20th century – and the FAA rules have been extremely effective – electrical system incidents do still occur on a routine basis. In addition, the Department of Defense has a variety of ongoing work related to improving wiring system design and developing new detection technologies [18]. However, the electronic detection of chafing and connector faults in practice, before consequences become noticeable, remains a significant problem still in need of enabling research.

> The Electrical Wiring and Interconnect System (EWIS) in any vehicle is a critical, and sometimes overlooked, avionics subsystem where relatively minor issues can grow and eventually lead to serious safety problems like smoke, fire, and loss of critical system functionality.

### 3.3.2   Avionics Emerging Factors

As aircraft become more electric, a range of avionic components and subsystems may generate new safety hazards, three of which are summarized below. Predominately, each of these have depended on the integrity of the wiring system for proper operation.

### 3.3.2.1    ElectroMechanical Actuators

Although ElectroHydraulic Actuators (EHAs) and ElectroMechanical Actuators (EMAs) are relative newcomers to the aviation industry, they are finding increasing use over purely mechanical hydraulic systems on aircraft, mostly because they compactly offer higher overall system performance and weight savings [19]. Furthermore, given that EHA's and EMA's have responsibility over manipulating the aircraft's control surfaces, failures of these systems have rather obvious safety consequences, and accidents have already occurred. One unfortunate case was Alaska Airlines MD-80 flight 261, where a horizontal stabilizer actuator failed due to insufficient lubrication and excessive wear of its jackscrew [20]. The aircraft crashed, killing all aboard.

### 3.3.2.2    Batteries

Depending on type, most modern aircraft employ batteries to start engines and auxiliary power units, to provide emergency back-up power for navigation units and fly-by-wire computers, and/or to provide ground power capability for maintenance and preflight checkouts. Newer "maintenance free" sealed-cell aircraft batteries are typically left on the aircraft for their fixed service lifespan of 2 to 5 years, with no scheduled maintenance during this period [21]. Thus, monitoring battery health for safety critical systems is necessary to detect incipient failure mechanisms and to actively ensure their availability when needed – especially for backup systems. In addition, unmanned aerial vehicles (UAVs) rely on battery power for flight control actuation when the main power source fails. Thus, reliable battery health management will be essential for safe operation of UAVs in the national airspace.

### 3.3.2.3    Avionics for Flight Automation

Flight critical avionics subsystems such as global positioning (GPS) and inertial measurement/reference units (IMU/IRU) are playing ever-increasing roles in many aspects of aircraft flight [22]. The common electrical failure mechanisms for these systems are capacitor and MOSFET (metal oxide semiconductor field effect transistor) degradation that can lead to glitches in the GPS position and velocity measurements. Other issues are loss of receiver lock on the GPS satellites along with IMU accelerometer and gyro biases [22]. Clearly, the measurements provided by these systems are critical to the proper operation of flight automation and management systems. Failures in these systems lead to unsafe and unintended automation commands and crew confusion. One example upset event, involving a Boeing 777-200 operating 240 km northwest of Perth Australia in 2005, occurred when a failed accelerometer component of an IRU and latent software errors ultimately caused the primary flight display to *simultaneously* indicate *both* a stall and over-speed condition. The aircraft pitched up into a climb while the indicated airspeed decreased from 270 to 158 knot. The stall warning and stick shaker devices activated. Fortunately, the aircraft was safely returned to the ground [2].

## 3.4    Propulsion Safety Factors

Aircraft engines are complex systems consisting of static and rotating components, along with associated subsystems, controls and avionics. They are required to provide reliable power

generation over thousands of flight cycles while being subjected to a broad range of operating loads and conditions, including harsh high temperature environments. Reliable operation of these engines is critical for aircraft safety. Over repeated flight cycles, the life of many engine parts may be degraded, and engine malfunctions may occur. Other events related to the environment such as bird strikes, volcanic ash, or icing may affect and degrade engine operation. Engine maintenance is primarily performed on a schedule, rather than based on the condition of the engine. However, ground-based inspections or standard maintenance operations cannot identify all the problems that can potentially occur in-flight. Overall, ensuring propulsion safety requires a multi-faceted approach, which includes design, certification, airworthiness directives, pilot training and awareness, inspection, maintenance, overhauls, condition monitoring, etc. The role of the propulsion system in aviation safety can be examined by reviewing historical aviation safety data and considering anticipated future safety challenges.

### 3.4.1 Propulsion Historical Data

Past technology advances made by the aviation community have resulted in aircraft propulsion systems with excellent safety and reliability records. However, Propulsion System Malfunction (PSM) still contributes to a number of aviation safety accidents and incidents. A review of global fatal aviation accident casual factors, including PSM casual factors, has been reported by the Civilian Aviation Authority [3]. Figure 3.4 breaks down the causal factors for fatal accidents further into primary and contributing factors. This figure illustrates that while the engine is less frequently the primary causal factor in fatal accidents, it often plays a significant role as a contributing factor.
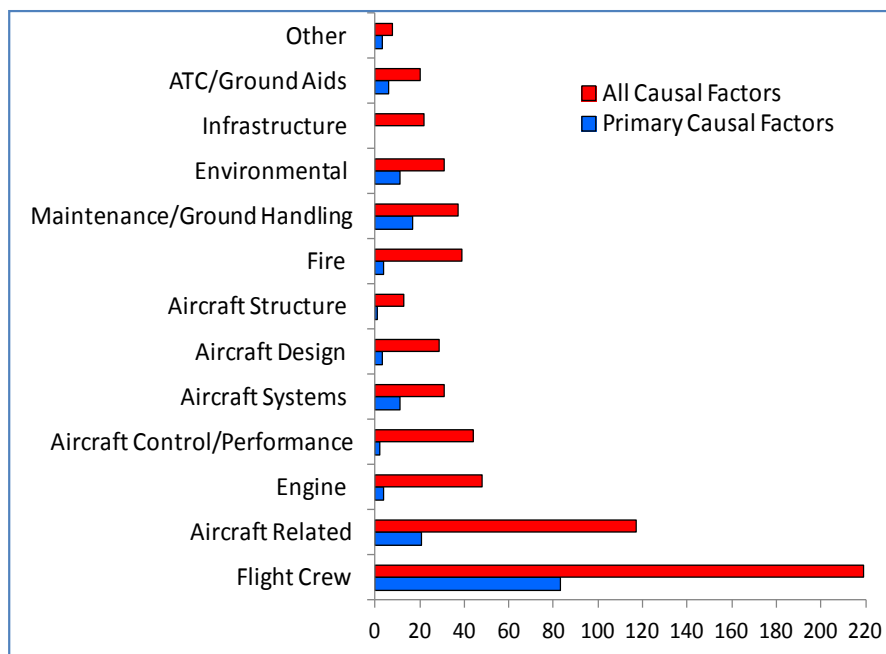


Figure 3.4.—Breakdown of all fatal accidents by causal group (showing all causal factors (red) and primary causal factors (blue)). Propulsion system malfunction as significant contributing factor to events in aviation safety [3].

Engine primary causal factor events are often due to uncontained rotor failures resulting in the uncontained release of high kinetic energy debris [23]. These can cause catastrophic damage to the aircraft structure and systems, negatively impacting the controllability of the vehicle, and/or resulting in serious injury or fatalities to the vehicle occupants. Additionally, environmental causal factors such as icing, volcanic ash ingestion, or bird ingestion can cause single-engine or multi-engine power loss events.

Engine contributing factor events are cases where propulsion system malfunctions are one of a combination of causal factors leading to the accident. For example, an aviation accident or incident may occur when a single benign propulsion system malfunction, not normally considered a significant safety concern, occurs coupled with the pilots' inappropriate or lack of response to the malfunction. Likewise, a single propulsion system malfunction may cause other events or malfunctions to which pilots' could respond inappropriately. Such a series of events, termed Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR), is frequently a contributor to aircraft accident and incidents, including loss of control (LOC) accidents. For example, "*A consistent contributing factor in PSM+ICR events is the lack of crew awareness of the existence, location, or type of the PSM, i.e., there is no clear, explicit indication or annunciation of the engine malfunction or the affected engine(s). In many cases, even when the crew is aware a malfunction exists, they are unaware that it is propulsion system related..*" [24].

The causes of PSM can be wide ranged. The propulsion system is composed of numerous moving and static parts and functionalities operational over a wide range of conditions. The high pressure compressor (HPC) or turbine (HPT) may operate at high temperatures with a high-speed rotation, while the lubricated components such as bearings or bearing seals operate in more benign environments but under high stress and they must maintain their integrity for proper engine operation. Malfunction or failure of these components can cause in-flight engine damage, in-flight engine shutdown (IFSD), or even unscheduled engine removal (UER). In general, monitoring across the whole engine is a notable challenge covering a range of operational conditions, and would be needed to fully monitor the wide range of potential failures. However, there are areas of the engine and its operation that stand out.

Figure 3.5 examines the contribution of various propulsion system components/subsystems to engine damage and ICR [25]. Notable contributors are gas path and lubricated components. To summarize, "*These results suggest that improved damage detection for gas path and lubricated components would also address the majority of the indeterminate cause events.*" One complicating factor in achieving improved damage detection is the contribution of sensor failure leading to in-flight shutdowns even in existing engine monitoring systems. Similar results are seen in military aircraft where turbines, bearings, and compressors are components with the greatest component costs associated with mishaps in class A and B engines [26].
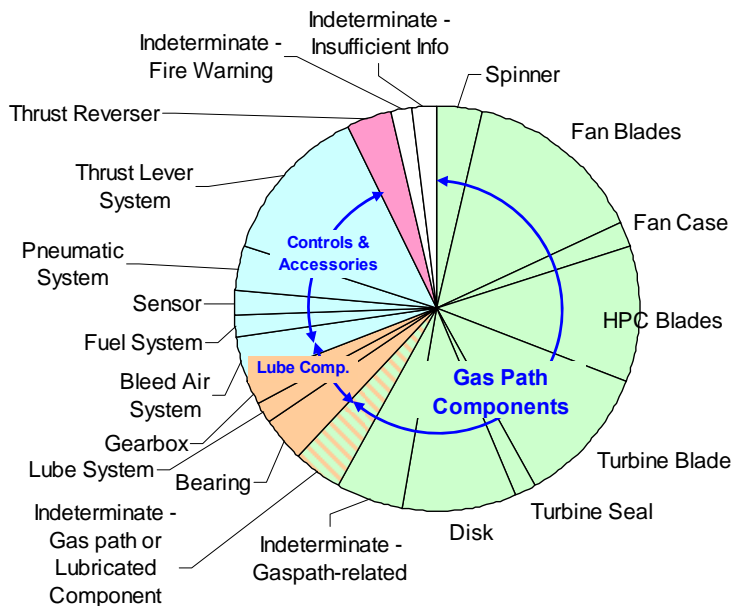
Figure 3.5.—The relative contributing factors of various propulsion system related components and subsystems to Engine damage during inappropriate crew response (ICR) events [25].

To summarize, the propulsion system is composed of numerous rotating and static parts and accessories operational over a wide range of conditions including harsh high temperature and high stress environments. The cause of PSM can vary across the range of these propulsion system component parts. Catastrophic engine failure events are rare, and when they do occur are often due to uncontained rotor failures. Gas path components, as well as the lubrication system/lubricated components, stand out as strong contributors to IFSD and engine malfunctions. Sensor reliability is a major issue for in-flight shut-downs.

### 3.4.2   Propulsion Emerging Factors

Propulsion systems have undergone significant changes recently in order to realize improved efficiency. Two of the new technology developments that directly involve the use of new material systems are 1) composite engine containment systems and 2) higher temperature alloys for turbine blade fabrication. Each of these material changes were made with improved efficiency in mind to reduce the weight of the propulsion system and to increase the operational temperature of engines. As with the introduction of composite materials for primary airframe structures, more pervasive use of composites across the vehicle, including potentially closer to the hot sections "…may have inherently different safety implications that will drive how we treat aging aircraft…[5]". The use of these materials requires knowledge of how they perform in service and what effect the new operating (i.e., higher operating temperature) conditions will have on the long-term behavior of these materials. Further, the move to more electric propulsion systems or Distributed Engine Control may suggest the use of electronics and control systems in environments beyond that of traditional technologies [27-28].

Aircraft propulsion systems are complex and subjected to a broad range of operating environments. Reliable propulsion system operation is core to maintaining overall vehicle safety. Propulsion system malfunctions can contribute to inappropriate crew response or loss of control related aviation accidents.

## 3.5    Brief Summary of Factors Influencing Aviation Safety

### 3.5.1    Vehicle System Summary

- Highly reliable aircraft systems and components do experience failures and malfunctions that contribute to aviation accidents and incidents.

- The combination of system and component failures combined with inappropriate crew responses and loss of control are notable contributors to accidents and incidents. Providing the crew with reliable, accurate information as appropriate can improve crew response in hazardous conditions.

- New materials and technologies will be incorporated into aircraft designs for a range of reasons. However, with the introduction of these new technologies, existing safety levels must be maintained or improved upon.

- Because there are multiple accident and incident causes across a vehicle that can be interdependent, safety system challenges and solutions vary between the subsystems, but must combine in a whole vehicle.

- Vehicle health assurance technologies will have to evolve to keep pace with the system-level effects of increasing number of flights, the integration of new technologies, and an operation beyond standard design limits or lifetimes.

- Maintaining vehicle safety does not begin when a vehicle enters into service, but is a life-cycle process starting from the design phase and extending throughout the lifetime of the vehicle.

- The capabilities for next generation design tools, vehicle inspection, and on-board health state awareness that are now applied in standard operation is limited.

### 3.5.2 Airframe Summary

- The airframe composes the majority of the aircraft structure. The existing fleet is predominately metallic based with a significant amount of previous history.

- However, this fleet is aging and long-term operation without a complete history of the stress loads that the structure has been exposed to may lead to unexpected structure failures.

- Unanticipated conditions and use of the vehicle in ways not intended in the design phase can occur that lead to excessive stress loads and operation beyond standard limits. Such conditions can lead to structural degradation and potential safety hazards.

- The use of composites in primary aircraft structures is a paradigm shift in aircraft structures. The properties of composites are not as well understood as in the corresponding metal systems.

- The introduction of composite airframe structures presents elevated safety risks due to complexity of the material systems and failure modes, potential variability in strength properties, and lack of experience in composites in commercial operations, inspection and repair.

### 3.5.3 Avionics Summary

- The electrical wiring and interconnect system is a core avionics component affecting nearly all avionics equipment. It is also a common point of failure that can bring down critical systems, and cause failures in multiple subsystems, through opens, shorts, arcing, and electrical fires.

- Wire chafing is a dominant precursor failure mechanism, which when detected early can enable preventative maintenance long before safety becomes an issue.

- Future aircraft systems will require more wiring to support additional functionality. Some of the wiring will be high-power, which introduces new fault possibilities.

- Future flight critical avionics systems are emerging, including electromechanical and electrohydraulic actuators, batteries (especially as the industry moves closer to the all-electric aircraft), and newer information systems, such as GPS, to support automated flight-management.

- Failures in these systems can have dire consequences but the health management capability to help prevent accidents resulting from the increasing complexity is limited.

### 3.5.4 Propulsion Summary

- The propulsion system is complex with multiple operational regimes. Rotating and high temperature components, and the lubrication system and lubricated components, are specific propulsion subsystems that can yield propulsion system malfunctions.

- Environmental effects, such as icing and bird ingestion, can lead to single-engine or multi-engine power loss.

- Propulsion system degradation and damage that develops over time in hot section components can lead to in-flight shutdowns. Events such as uncontained rotor failures can lead to catastrophic failure.

- Sensor reliability is a notable challenge in part given the operational environments.

- Propulsion system malfunction plus inappropriate crew response is a significant aviation safety concern.

- Emerging factors such as the use of composite engine materials and the operation of engines at higher temperatures can have notable impact on engine safety.

- Improved detection and diagnosis of incipient engine faults in the early stages can help mitigate the safety impact of component failures that do occur.

## 4.0    Present State-of-the-Art of Vehicle Health Assurance

Section 3.0 described the factors influencing aviation safety as a combination of both vehicle and subsystem challenges. In particular, there is an interrelation between subsystem and vehicle health, as well as between subsystems. In order to understand how aviation safety can be improved, this section gives an overview of the present state of the art in vehicle health assurance both on the vehicle and subsystem level. This overview is not exhaustive, but is meant to provide an understanding of the framework and approaches to present vehicle health assurance and provide a foundation for possible future advancements.

## 4.1    Vehicle State-of-the-Art

The present state-of-the-art (SOA) in overall Vehicle Health Assurance is summarized in Figure 4.1. It can be considered an approach that has been notably "stove-piped" into three separate components during the evolution of flight systems and complementary technologies. These components of the present Vehicle Health Assurance approach include:

1) Design and testing;

2) On-Vehicle Monitoring; and

3) Ground based maintenance.

These components of present vehicle health assurance are evolving over time, but a snapshot of the approach for each section of the block diagram in Figure 4.1 is described very briefly below.

### 4.1.1   Design and Testing

The design of aircraft systems has a long and successful history. This design process includes the use of known materials with well-understood properties, extensive modeling and life prediction, and following the certification procedures set forth by the Federal Aviation Administration (FAA). However, aircraft are being extended past their design life and as noted by Tiffany et al. [4] "as aircraft structures are used beyond their initial intended design life goals, new unidentified cracking sites and cracking behaviors are again leading to new catastrophic structural failures". While safety of the vehicle is strongly considered in the design stage, this is predominately done historically by adjusting design margins. Design margins are purposely targeted with the understanding that during operation limited information on a number of vehicle state parameters will be available. Thus, vehicle systems can be, effectively, "overdesigned" to allow for a built-in safety margin. Although there are number of sensors built into the aircraft and used for control and operations, the addition of a comprehensive Vehicle Health Management system is typically not part of the design process. Rather, implementation of Vehicle Health Management is carried out after the design phase using the existing sensor and avionics infrastructure. In general, Vehicle Heath Management is integrated into the vehicle as an add-on rather than a core design consideration.
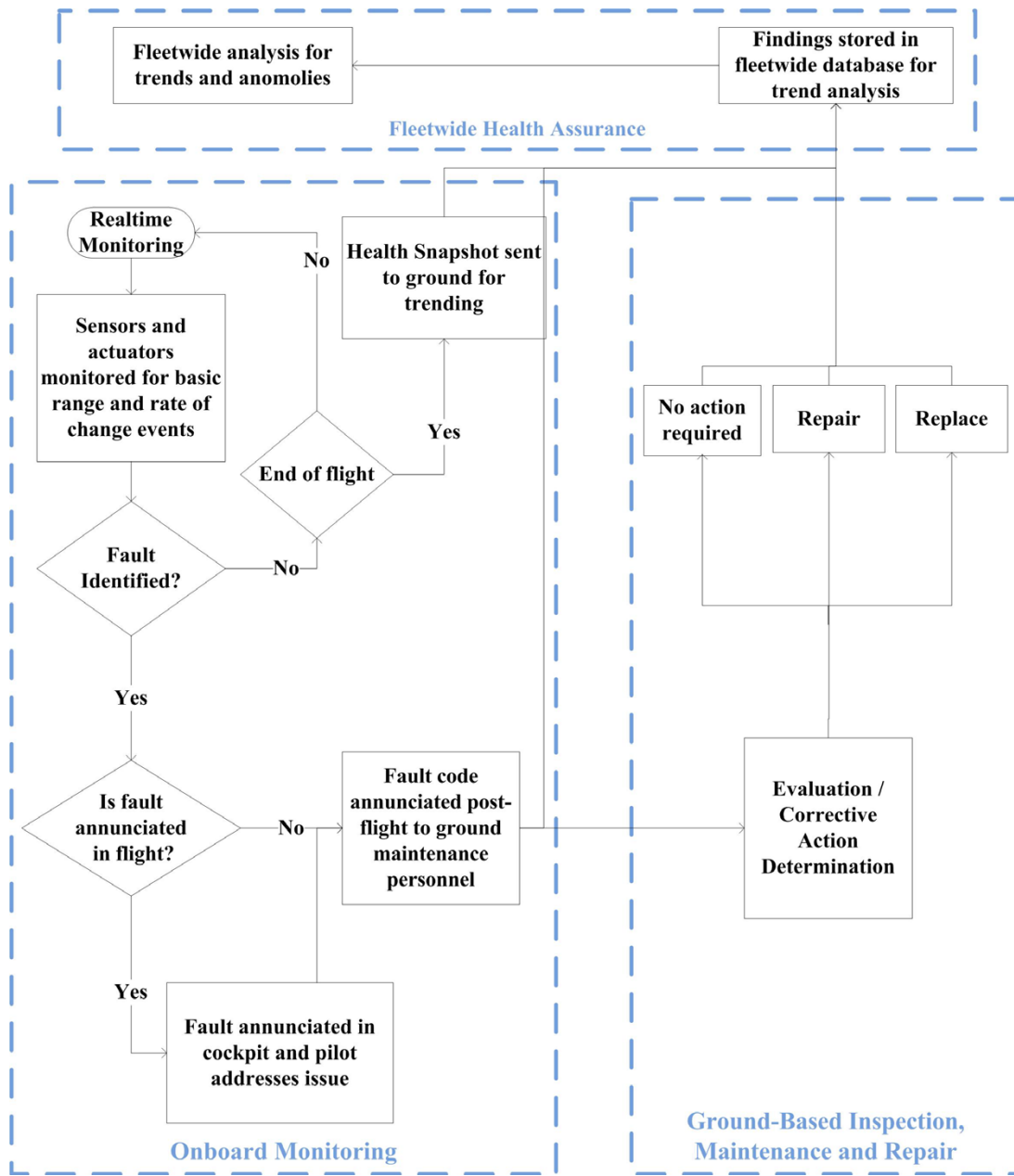
Figure 4.1.—A simple overview of the present state-of-the-art (SOA) in Vehicle Health Assurance.

## 4.1.2 On-Vehicle Monitoring

The vehicle operational sensors do provide a notable amount of information related to the vehicle operation. In contrast, the number of sensors and on-board diagnostics implemented solely for health management purposes is presently limited. A significant amount of operational information has been available, but the amount of information that is relevant to health management varies among the multiple subsystems (see the discussion in Sections 4.2 to 4.4). There has traditionally been a limited amount of information that is fed in real-time to the ground operations. Recently, more advanced on-vehicle health monitoring systems have begun to expand what is available for health assurance purposes. Such capabilities include the ability to

have a selected number of in-flight faults, customer-specified alerts, and simple text information (Aircraft Communications Addressing and Reporting System or ACARS) communicated to the ground [29,30]. The amount of data transmitted is limited, if for no other reason than the huge amount of data available, and challenges in transmitting such large amounts of data in-flight. Upon arrival, further information can be provided to ground maintenance. Examples include the data associated with tire pressure, oxygen pressure, hydraulic fluid, and engine oil levels. Again, a notable challenge is proper infrastructure for the handling of the large amount of data available in an effort to improve the safety, as well as the efficiency, emissions profile, and performance of the aircraft.

### 4.1.3   Ground-Based Maintenance

Vehicle inspections are initiated if an on-board alert or potential issue has been identified, or as part of a standard maintenance schedule. Inspections are performed either visually or using non-destructive evaluation (NDE) techniques. The information provided by these inspections is compared to fleet wide averages and used to identify potential issues in the health of component parts. If an issue is identified, the ground crew can repair or replace the affected component, or plan to simply monitor the situation. The fundamental aspect of ground maintenance is that it is typically performed to a schedule, or if an inspection is warranted by a trend or alert. This schedule is set forth by the manufacturers and the regulatory agencies to maintain the continued airworthiness of the vehicle. This maintenance may include operations or replacement of parts not mandatory given the state of the individual vehicle, but dictated by the maintenance schedule for vehicles of this type. It is not performed as needed based on individual vehicle life history (condition-based maintenance).

A fundamental aspect of this present approach is its centralized nature. This centralized nature is limited in its ability to ascertain the specific health state of the vehicle. Large amounts of data are stored in centralized locations with limited pre-diagnostic processing. The on-board information transmitted in-flight to the ground is prioritized and constrained by processing and bandwidth restrictions. The sensor data tend to be based on sensors initially intended for vehicle operation, and are not targeted directly towards health monitoring or emphasize on-board diagnostics or prognostics processing. Maintenance is predominately on-schedule based on past fleet history, not the vehicle's condition.

These trends are reflected on the subsystem level. A challenge is to ensure that disparate subsystems report associated faults according to a standard protocol that allows for proper processing and system-level health determination. The methods used for subsystem health determination vary depending on the type of measurements available to extract fault signatures. Typically, instrumentation suites are limited due to weight and processing constraints and provide only high-level fault indications. A discussion of the SOA for airframe, avionics, and propulsion is presented below.

## 4.2    State-of-the-Art in Airframe Health Assessment

Today, aircraft structural health is generally managed through a series of inspections. Regular visual inspection is performed prior to each flight by the aircraft crew. More detailed scheduled inspections occur at specified intervals based on aircraft certification requirements and fleet history. Additionally, unscheduled detailed inspections can be triggered by a known event such as a bird or lightning strike or as the result of crew findings. Visual inspection of components for damage of the structure is the primary nondestructive inspection (NDI) method used. Regulatory bodies have issued formal descriptions for both visual examinations and for all NDI. Visual inspections are much more common and comprise the majority of all aircraft inspections (approximately 80% [31]). It consists of using the inspector's eyes, often aided by magnifying lenses and supplementary lighting, as the detection device. Inspectors must visually scan the whole structure of interest, typically using portable mirrors to examine areas not directly visible. Once damage is observed, a sequence of discrete steps is initiated including: quantification of the damage by advanced nondestructive evaluation (NDE), engineering analysis of the significance of the damage to the structure (typically based on damage size and location allowables determined by initial testing and analysis during aircraft design and certification), and disposition of damage as either requiring repair or "safe-to-fly."

While this reliance on visual inspection works well for relatively large-scale damage, each of these steps has a level of inherent risk, including risk introduced by human factors that cumulatively could reduce the margins of safety associated with the structure. In addition, subsurface or small-scale surface damage may be dismissed or go undetected. For composite structures, the current design practice is to set the inspection threshold at barely visible impact damage (BVID), any damage smaller than BVID is not considered to affect the safety of the structure. Today, for all material types, both the allowable damage limits and critical damage size are determined primarily through extensive coupon, subcomponent and component level testing [32]. In practice, multi-site damage may be sufficiently close as to interact with each other or with other types of damage leading to unanticipated reduced margins of safety. These include multiple fatigue cracks in metallic structure, or low energy impact damage, which for composite structure is below that which results in BVID.

NDI procedures and their inspection intervals are documented in the maintenance technical manuals associated with each aircraft [33]. The inspection results are recorded, either manually or electronically, and kept with the associated aircraft throughout its service life. Current protocol utilizes the inspection data in order to make case-by-case decisions regarding the specific component. Airframe components are managed using a damage tolerance approach. Damage tolerance components are managed using periodic inspections based on fatigue crack growth predictions [34]. The results of each inspection are used to determine if the existing damage is safe for operation until the next scheduled inspection. If the damage is benign, no action is necessary. If the damage may result in a safety concern prior to the next inspection, then the component may be repaired or refurbished if a certified process exists, or may require replacement if no certified process exists or if the damage is determined to be too extensive [35]. Inspection criteria based on damage tolerance predictions have been adjusted based on

operational history, allowing for a reduction in applied factors of safety without reducing the actual operational safety of aircraft. This has proven to be an effective and safe approach since the implementation of damage tolerance approaches in aircraft management, as airframes have only undergone incremental changes. However, with the introduction of composite materials in primary structure and the widespread insertion of new aluminum-lithium alloys, less is known about the long term performance of these materials thereby requiring the application of higher factors of safety than are used for most current aircraft. For fracture critical components (e.g., within landing gear or turbine engines), replacement is the only course of action upon finding a flaw.

Fracture critical components are defined as components whose failure represents a hazard to the entire aircraft [36]. Currently, fracture critical structural components within commercial aircraft are designed based on the safe life approach [37,38]. Within the book life or within a specified inspection period, whichever is less, a damage tolerance fatigue crack growth analysis must be performed to determine whether the component has adequate margin for failure from material, manufacturing, or service induced flaws or cracks. The safe life approach states that a component should be retired when the book life is reached, or when there is an inadequate fatigue crack growth margin prior to the next scheduled inspection. The book life for a component expected to fail due to crack growth is based on the number of fatigue cycles to crack initiation. For the case of a commercial aircraft turbine component that is designed for low cycle fatigue, a cycle is considered one complete flight that includes take-off, cruise, and landing. When designing a safe life component, stresses are obtained by conducting a finite element analysis with load and temperature inputs based on assumptions, tests, and previous experience. Material properties (e.g., fracture and creep resistance) are based on an extensive specimen scale data base. To account for load, environment, and material variability as well as deficiencies in design tools, a statistical rule is typically applied [39]. As is the case for the insertion of new materials in a damage tolerance design, the use of new materials in safe-life designs where there is little to no operational history requires the use of more conservative design margins. It is necessary to monitor new materials closely and evaluate design criteria as an operational history is established.

As described above, aircraft operators rely on visual and relatively simple inspection tools for assessment of airframe health. Due to the costs associated with advanced NDI tools, operators are reluctant to purchase all but the most simple inspection tools. For this reason, current tools have been developed that are simple to use and relatively inexpensive. For example, General Electric and Boeing jointly developed a probe system for 787 airframe inspection [40]. The probe provides a pass/fail indication after the probe is calibrated using a calibration block of properties suitable for the inspection location. This tool still relies on the operator to map the defect in order to determine size. While scanning systems have been developed [41], cost can be prohibitive for operators. Although some work has been done, overall, Structural Health Monitoring (SHM) is limited in sensor requirements, standards, and polices, which leads to variability in product development and demonstrations [42]. Although SHM systems have many

potential benefits, they are typically demonstrated by monitoring a hot spot where damage already exists or is likely to form [43].

The Aerospace Industry Steering Committee on Structural Health Monitoring and Management (AISC-SHM) is working on a document "SHM guidelines for aerospace" to address an overall SHM approach. The document is targeting a 2012 release date. The team includes the large aircraft manufacturers Boeing and Airbus, and NASA. This group is "an international team comprising industry, government and academic participants with a collective vision to efficiently and effectively implement structural health monitoring for a wide variety of commercial and military aerospace applications through the development of guidelines, procedures, processes and standards for implementation and certification of the technologies." [44]. Aviation Week picked SHM and Aircraft Health Monitoring as 2nd and 3rd on their list of 10 technologies to watch in 2011 [45].

> The SOA in Airframe Health assessment is dominated by significant reliance on visual inspection followed by NDE techniques as problems are identified. A safe life approach is used in the design of component materials, which includes a set lifetime for component parts.

## 4.3 State-of-the-Art in Avionics Health Assessment

In this section we briefly review the current industrial capability and emerging technology most relevant to the health management of the safety critical electrical systems identified earlier in this report. First, Electrical Wiring is discussed, and then a range of other avionics systems.

### 4.3.1 Electrical Wiring and Interconnect System (EWIS)

The current FAA rules for EWIS design, recently updated in November 2007, take almost every practically feasible precaution to ensure best practices for wiring system *design and maintenance* are followed [46]. However, there are currently no automated non-destructive evaluation methods required to ensure that these systems remain safe between regular inspection intervals, and in part this is because the required technology either does not yet exist or is not yet mature enough.

### 4.3.1.1 Test Equipment

The industry standard method for detecting and diagnosing wiring issues is Time Domain Reflectometry (TDR). This technique works by first inducing an electric pulse on a target wire, and then analyzing the reflected response for anomalies that may be indicative of a fault. The distance to fault is determined by timing the return of the fault's reflection relative to the incident pulse, the speed of propagation, and the length of the wire. The phase (or sign) of the reflection distinguishes between open and short conditions.

Although TDR is viewed as an industry standard, the reflection results can be difficult to interpret and the technology has so far found success primarily in the ability to detect hard open

or short circuits, as can be seen, for example, in the 2007 FAA study of currently available off-the-shelf systems [47]. There are several well-established manufacturers of TDR test equipment for use in the aviation industry [48-50]. There are also a wide variety of variations on the TDR method, such as Frequency Domain Reflectometry (FDR), Time-Frequency Domain Reflectometry (TDFDR) [51,52], Spread-Spectrum TDR (SSTDR) [53], Pseudo-Random Binary Pulse TDR, Broad-Band Impedance Spectroscopy [54], and Excited Dielectric Test [55] methods. Each of these methods employs essentially the same physical mechanism where an input voltage signal is applied (but different in each case) and the cable response is measured and analyzed through a variety of signal processing techniques, both basic and advanced. Finally, we mention here that approaches to new wiring designs that enhance TDR based fault detectability (as well as self-healing materials) have been investigated as well [56].

Another fundamentally different technology offered by industry for diagnosing wire faults, including some types of intermittent and chafing faults, are Low Energy High Voltage (LEHV) and Pulse Arrested Static Discharge (PASD) systems. In LEHV, the target wire is slowly charged until an arc-event occurs at the fault location. In PASD a short high voltage pulse is launched onto the wire, at increasing amplitudes, until a breakdown occurs at the fault location [57]. In both cases, the wire fault is located by processing the arc-event waveform measured at the source. Both of these technologies are only applicable to un-powered wires, require relatively small air gaps between the powered and grounded conductors (so that an arc *can* occur), and are sensitive to environmental factors like humidity. It is also difficult to prove these technologies do not degrade wire performance over long term extended use. Two manufacturers have teamed to offer a single wire integrity test tool that combines the latest high-voltage and TDR based test technologies [58]. Other companies offer complete ground based wiring system analysis capabilities that combine the many different technologies to perform continuity, insulation, and isolation tests [48].

Finally, at least one company [59] has also developed a fiber optic wiring degradation detection system combined with a diagnostic and prognostic monitoring system. This consists of multiple optical fibers strung with the harness. Should the harness suffer pinching (e.g., clamps that are too tight, poor hatches) fiber(s) would be damaged and therefore the point of damage could be determined with the use of optical domain reflectometry. A more extensive summary covering many of these variants and more is presented in [14].

### 4.3.1.2    Wiring System Design/Analysis Tools

Companies also provide assessment software capabilities to ensure the FAA wiring system design rules are met given routing and zoning (relative areas on the physical structure of the aircraft) information [60]. In particular the process helps to assure adequate separation and segregation of aircraft wiring, thereby minimizing the potential for a single failure to have catastrophic consequences. Additional services including aircraft wire management systems, arc damage modeling tools, risk assessment and service life extension programs are also offered.

#### 4.3.1.3 Emerging Wiring Technologies

In addition to the established regulations, inspection, and software tools mentioned above, a variety of new hardware capabilities relevant to built-in online wiring system health management are emerging. In particular, the following relatively new developments along with NASA's contributions (discussed later) hold promise for enabling automated preventative fault detection for the most critical wiring on an aircraft.

- New solid-state power controllers and distribution systems are replacing mechanical circuit breakers and relays in new aircraft, while at the same time shortening wire lengths and simplifying much of the wiring system design. Specific examples include the Boeing 787 [61], and the Gulf Stream G650 [62]. In addition, these power controller systems can provide arc-fault detection, electrical load protection, monitoring and shedding, *and even some diagnostics and prognostics capabilities—possibilities include incorporating line replaceable unit (LRU) feedback and the trending of load current and power usage with time for example.*

- Small (1- by 1-cm) Spread-Spectrum TDR integrated circuits (ASICs) are now just emerging that have the potential to be embedded into a variety of systems, including connectors, for online intermittent fault detection in possibly high noise environments [58].

### 4.3.2 Other Avionics Systems

Health management for avionics of aircraft has evolved greatly from the earliest push-to-test built-in test equipment (BITE). Many aircraft today employ a centralized computing system that gathers fault indications from modular subsystems, performs root cause diagnostics, and recommends maintenance actions. The root cause determination is performed with the aid of models that encode the propagation of fault effects to observable symptoms. Model information is contained in a database that can be updated and loaded to the monitoring system without requiring changes to the functional code [63].

However, components that are critical to the proper operation of safety-critical avionics, such as the power semiconductors and capacitors that can, for example, affect navigation equipment, are not instrumented to the degree that enables detection of failure precursors. Until recently, it was believed that there were no indications of impending failures in these components. This turns out not to be the case, and similar to mechanical systems, electronics undergo a measureable wear process from which one can derive features that can be used to provide early warnings to failure [64].

#### 4.3.2.1 Electromechanical Actuators

Health management for electrohydraulic and electromechanical actuators (EHAs/EMAs) is an emerging field that is rapidly gaining importance as newly designed commercial aircraft are developed. For example, the Boeing 787 and Airbus 380, use more EMAs in roles traditionally reserved for purely mechanical hydraulic systems. Even though EMAs have been studied

extensively from a functional point of view—in order to help develop new and improved designs—studies from a health management point of view have been rather limited. The reason is largely attributed to unavailability of operational fault data from fielded applications. Because of this, early research efforts conducted by industry and government partners have focused on identifying critical fault modes and the development of EMA fault testing and aging capabilities in the lab; along with the fault diagnostics and prognostics methods needed for health management. Below we provide a brief synopsis of current developments detailed in [65].

Initial and ongoing industry efforts have focused on developing accelerated aging and test methods for EMAs in a lab environment. In some cases, test rigs were developed to allow for fault injection covering a wide spectrum of electrical, mechanical, and sensor faults. Particular faults frequently studied include: spalling, backlash, ball return jam, and stator coil failure (not to mention wire chafing and connector issues) to name a few. See [19] for a full summary. Aircraft original equipment manufacturers (OEMs), like Boeing, have also shown considerable interest in developing EMA health management technology. In one collaborative effort between Boeing, Air Force Research Lab (AFRL) and Smiths Aerospace in 2006, an Aircraft Electrical Power Systems Prognostics and Health Management (AEPHM) system was developed to address faults in electric actuation among other things. One conclusion from this study was that the existing indicators had limited sensitivity to be able to distinguish between various EMA fault modes and more investigation was required to determine the appropriate sensor suite and signal processing methods. Finally, companies like Ridgetop Technologies, in collaboration with NASA, have focused on developing health management methods for power electronics components of EMA systems.

Diagnostic health management algorithms for EMA and EHA fault detection are broadly divided into two types: model-based and data-driven. Model-based schemes rely on system models developed from the underlying knowledge about the system and how it works (using physics for example), while data-driven schemes do not require such models but instead require large sets of exemplar failure data, which is often not available. For example, current and voltage sensor outputs in an EMA can be modeled using physics-based differential equations, which in turn enable model-based diagnosis of faults. On the other hand, modeling accelerometers is better suited to a data-driven, feature-based, diagnosis approach. Thus, the current overall approach to EMA diagnostics synergistically combines the model-based and data-driven diagnosis techniques. Example approaches for both EHA/EMAs are presented in [65, 66].

### 4.3.2.2    Batteries

Health determination for aviation batteries is typically to the level of pass-fail tests to determine whether to replace the batteries. Measuring the open circuit voltage, which is applicable only to sealed lead-acid batteries, is the simplest method but also the least effective as it determines the state of charge rather than the state of health. For rechargeable batteries, discharging to a fixed cut-off voltage generally provides a more accurate measure of battery capacity. However, this typically takes several hours, requires removing the battery from the aircraft, and requires special support equipment—hence it is impractical. Alternatively, the battery voltage can be measured

in-situ while subjecting it to a load for a short period of time. This is more practical but does not indicate the reserve capacity of the battery [21]. Another method is to use electrochemical impedance spectroscopy, which avoids having to load the battery but requires special equipment. Conductance testing can also be combined with sensing other battery parameters such as temperatures and the amount of float charge [67].

Recent research has gone beyond a pass/fail diagnostic state assessment to exploring the practicality of predicting end of life for batteries. Based on end user requirements and available resources, different techniques of varying complexity may be appropriate. For situations where the rate of capacity degradation is slow, simple regression methods can perform well as more data are accumulated and predict far enough in advance to avoid catastrophic failures. When accuracy and precision of predictions are important, more sophisticated techniques that employ underlying physical models perform better at the expense of computational complexity [68].

> The State-of-the-Art in Avionics Health management involves a limited amount of automated flight and ground capabilities, although a number of systems are not monitored even as the vehicle becomes more electric. In particular, wiring is the core of the avionics system with limited capabilities for on-board inspection.

## 4.4  State-of-the-Art in Propulsion Health Assessment

Engine Health Management (EHM) systems are typically more complex than health managements in other subsystems. This section describes EHM systems that assist aircraft operators in managing the safety, availability, and affordability of their propulsion assets. The functionality of the EHM system has some notable features beyond health management in other subsystems. The functionality provided by an EHM system includes monitoring, detection, isolation, and providing recommended inspection and maintenance actions to address deterioration, faults and failures. EHM systems are unique, and vary in their design dependent upon the application needs of the end user [69]. Figure 4.2 shows a representative EHM system architecture. Here, both onboard and off-board (ground-based) EHM functionality are shown. Onboard, an Engine Monitoring System (EMS) acquires data and performs built-in-tests and other engine monitoring functions such as detection and status assessment. Taking a broad definition of EHM, the onboard system can also be viewed to encompass functionality such as engine control fault detection, isolation, and accommodation logic as well as cockpit alerts, indications and warnings. Onboard information is transferred off-board to a ground-based EMS through a data link. Ground-based functionality includes fleet-wide engine trend monitoring and fault diagnostics. This information is ultimately converted into actionable information used for maintenance and logistics planning purposes. This can range from replacing a line replaceable unit on the flight line to conducting a complete engine overhaul.
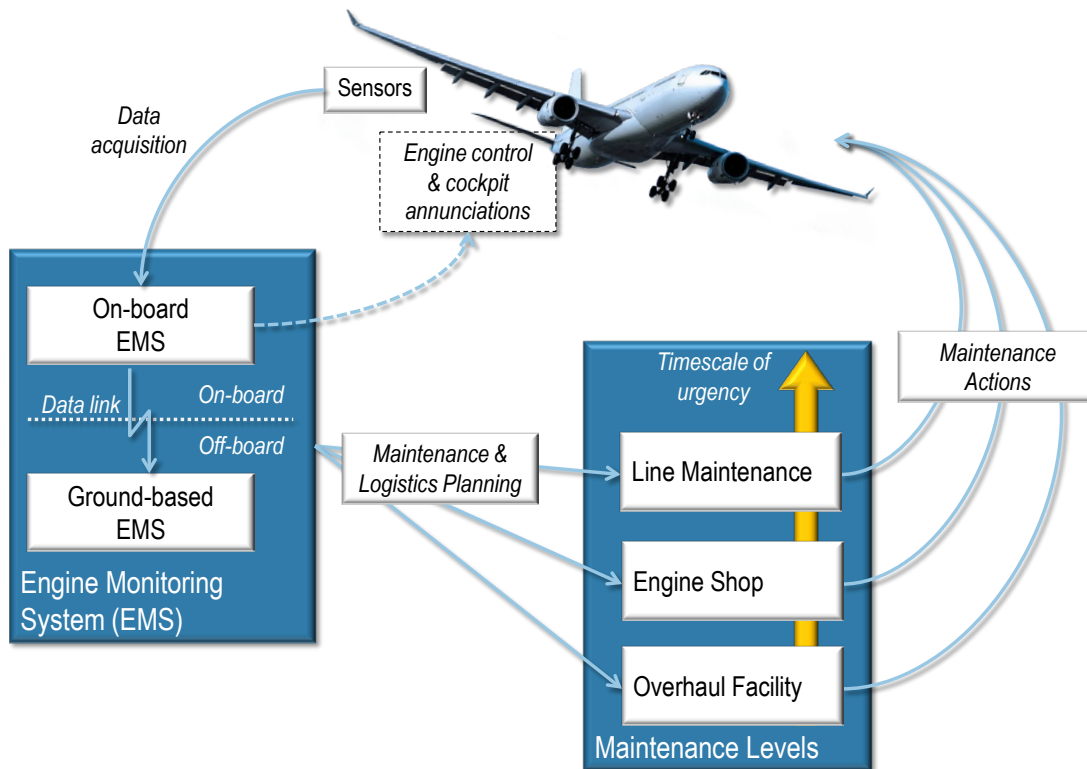
Figure 4.2.—Engine Health Management System architecture.

### 4.4.1 Maintenance Levels

In order to prevent accidents between major inspections, an understanding of how maintenance is performed and on what schedule is necessary. The maintenance levels that are scheduled and performed differ in terms of their location, level of urgency, and required turnaround time [70]. These levels include:

- *Line maintenance*: Performed at the flight line by ground maintenance personnel. This involves basic troubleshooting, inspection and the replacement of line replaceable units. Often it entails maintenance issues that must be resolved in order for an aircraft to dispatch on its next flight. High urgency and short turnaround timeframes are common.

- *Engine shop*: On-wing engine maintenance performed at dedicated facilities. Engine shops are usually located at airports that serve as major airline hubs. They provide general engine maintenance services as well as more in-depth troubleshooting and repair. Depending on the urgency of the issue, an operator may choose to postpone maintenance until the vehicle can be flown to an engine shop site. This includes time limited dispatch faults, which allow an operator to dispatch an aircraft with known faults for a limited period of time before maintenance is performed. Often it is more cost effective to address such faults at a maintenance shop that provides the required personnel, tools, and replacement parts, rather than bringing those parts to a remote aircraft location.

- *Overhaul facility*: Overhaul facilities provide off-wing complete engine teardown, inspection, and overhaul services. This helps restore engine operating performance and it is critical for ensuring the integrity of engine life limited parts. Engines will undergo overhauls only a few times during their lifetime of use. Operators typically have long lead times in which to forecast and schedule these events.

### 4.4.2   Engine Monitoring System Functionality

Aircraft EMS functionality is multidisciplinary, spanning many technology areas as shown in Figure 4.3. A brief description of each of these technology areas is given below.
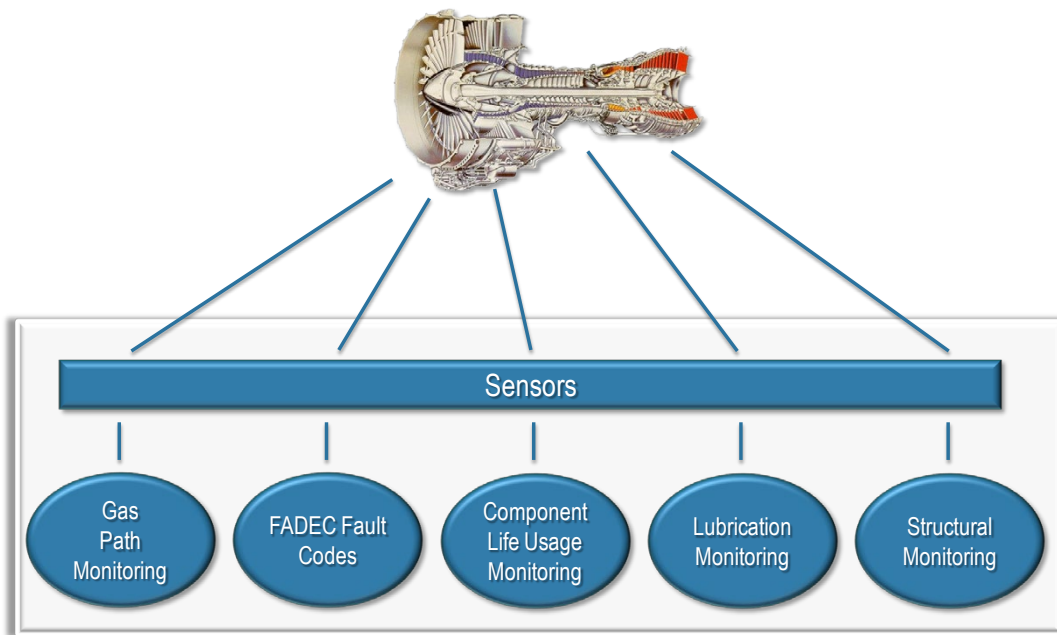


Figure 4.3.—Engine Monitoring System functionality.

### 4.4.3   Gas Path Monitoring

Gas Path Monitoring is associated with the health of gas turbine engine flow-path components and controls accessories [71,72]. It is performed by relating observed changes in sensed engine variables to internal performance-related changes within the gas turbine engine cycle. Monitoring and processing engine sensed measurements enables the detection and isolation of problems, ultimately enabling corrective action to be taken. Examples of the types of events that can be addressed by gas path monitoring include performance analysis of the major rotating modules of the engine, sensor faults, actuator faults, and turbomachinery damage. This monitoring function primarily relies upon the gas path sensors installed on the engine for control purposes. Historically, gas path monitoring came into prevalence concurrent with the introduction of digital engine controls and avionics. Prior to this, gas path performance trending was conducted manually based on cockpit gauge readings hand-recorded by pilots. The introduction of digital avionics and controls revolutionized this process by providing access to additional sensed measurements, along with automated data acquisition and processing

capabilities. This enabled the inclusion of on-board engine diagnostic functionality, as well as ground-based fleet-wide EMS functionality in computer ground stations, which processes engine data acquired in-flight.

### 4.4.4 Full-Authority Digital Engine Control (FADEC) Fault Codes

An EHM system can be considered to encompass the fault detection functions that are typically performed within the FADEC. An electronic engine control performs a number of checks for the validation of sensor measurement signals. This includes range checks, rate of change checks and cross-channel checks across redundant channels of a dual channel FADEC. This can aid in determining when an engine sensor is exhibiting anomalous behavior or failing. Checks on actuators, such as position feedback or current-loop checks, can provide independent information regarding engine health and the health of various engine subsystems. FADEC failure detection algorithms typically generate fault codes that indicate the presences of one (or more) of a list of pre-identified failure conditions. Operators must follow prescribed maintenance procedures and dispatch limitations pertaining to each specific fault code. This capability has only come into use with the introduction of electronic engine control systems. These FADEC fault codes provide relatively rudimentary diagnostic capabilities, although these capabilities have become more sophisticated over time.

### 4.4.5 Component Life Usage Monitoring

Component Life Usage Monitoring is applied to track the remaining useful life in life-limited engine parts. These parts must be inspected on regular intervals and replaced before their usable life is expended. Component lifing algorithms track part usage by effective cycle counting [73]. These algorithms track the number of acceleration/deceleration cycles a component has experienced, along with the severity of these cycles. For example, full-power engine takeoffs attribute to more life consumption than de-rated power takeoff cycles. Life usage monitoring is inherently tied to the disciplines of materials and structures. It enhances safety by enabling more accurate life consumption tracking, while also providing operating cost reduction by allowing extended component time on wing. A component lifing system functionality typically resides both on-board and off-board the aircraft. Often data is acquired onboard, then compressed and transferred off-board for further analysis and tracking.

### 4.4.6 Lubrication Monitoring

Lubrication System Monitoring in today's aircraft engines is often performed post-flight by Spectrographic Oil Analysis Programs [74] which analyze oil samples taken from the engine at specified intervals. Through this process the chemical composition of the oil is analyzed, and checks are made for the presence of contaminants or particles within the oil. Online monitoring capabilities often consist of oil debris monitoring systems such as chip detectors which monitor for the presence of metallic particles in the engine oil system. If fretting or spalling of engine mechanical components occurs, metal particles are generated and released into the system oil. The chip detector sensor contains a magnet to attract any metal particles that may be present in the lubrication system. When a particle becomes attached to the chip detector magnet an electrical circuit is completed and a warning can be generated to have the engine inspected. A

range of other parameters are monitored included oil level, temperature, pressure and filter delta pressure sensors as well as the ability to measure oil debris [75].

### 4.4.7  Structural Health Monitoring

Structural Health Monitoring for engines deals with the health of rotating gas turbine components, which present a dynamic structural health monitoring scenario. In the case of the Joint Strike Fighter F135 engine this includes a dedicated fan eddy current system that monitors the structural health of the fan blades [76]. The current SOA also relies on vibration sensors, which provide a vibration signature to detect faults within the rotating components of the engine. Perhaps the most advanced vibration monitoring systems are the current Health and Usage Monitoring Systems (HUMS) being flown on rotorcraft that focus on transmission and drive train monitoring. Today, commercial turbofan engines are typically equipped with relatively low frequency accelerometers that monitor for rotor out-of-balance and high vibration amplitudes. Higher frequency vibration analysis, which is being introduced on some military aircraft, has been enabled by recent advances in the fields of data acquisition and signal processing. Example candidate faults for detection via vibration diagnostics include bearing faults, turbine blade failures, gear failures [77], foreign object damage events, disk cracks, and shaft cracks. The vibration frequencies of interest to diagnose such faults are dependent upon the design and rotational speeds of the components of interest. For example, bearing defects (i.e., ball, inner race, and outer race faults) can be diagnosed by monitoring for periodic impacts, which occur at the ball passing frequency, which can be estimated from bearing geometry and rotating speed.

### 4.4.8  Sensors

Sensor technology is the foundation upon which EHM is based as it is relied upon to acquire the required data. Many of the sensors used for EHM today have multi-functionality. For example, the primary function of most of the sensors used for gas path health monitoring is for control purposes (i.e., pressure, temperature, rotor speeds, fuel flow, etc.). Dedicated engine monitoring instrumentation is included for the purpose of monitoring the fuel system (e.g., fuel inlet pressure) and the oil system (e.g., oil pressure, temperature and quantity). Additional instrumentation may also be included for monitoring engine vibration levels and lubrication system debris monitoring. Sensor technology in some locations within the engine is limited due in part to the extreme high temperature operating conditions.

### 4.4.9  Host Computing Platforms

EMS functionality resides in onboard and off-board host computers. For onboard host computers, this includes the electronic engine control computer, dedicated engine monitoring units, aircraft condition monitoring systems, or central maintenance computers. Key design considerations are data acquisition rates, processing speed, and memory requirements. Often this restricts the level of sophistication that can be implemented onboard. For off-board host computers, dedicated ground station computer systems are applied to host EMS functionality and archived fleet-wide databases. There are various approaches for transferring data off-board the aircraft. This includes wireless in-flight telemetry ACARS satellite communication, ground wireless communication, and manual physical transfer of data such as thumb-drives.

The State-of-the-Art in Engine Health Management involves a series of functionalities intended to provide health information on the complex engine system. Reports of the engine health state are provided post-flight, although visibility into the real-time state of engine health is limited, and engine parts are often replaced based on a schedule as opposed to condition.

## 5.0    NASA Contributions to the State-of-the-Art and Available Capabilities

Over many years and a number of programs, NASA has endeavored to advance the state-of-the-art (SOA) related to health management and safety technologies. This work has often concentrated on technologies, components, and subsystems; in general the state of art of vehicle wide health assurance is at an earlier stage of development. This section describes NASA contributions to the state-of-the-art and capabilities in both in the relatively newer field of vehicle wide health assurance, as well as in the various subsystems.

## 5.1    NASA Contributions to the Vehicle State-of-the-Art and Capabilities

One of the more recent examples of efforts to advance the state-of-the-art in vehicle health assurance is the NASA Integrated Vehicle Health Management (IVHM) project concluded in 2010. The NASA IVHM Project set out to validate tools and methods for automated detection, diagnosis, prognosis, and mitigation of adverse events during flight with the goal of reducing aircraft accidents and incidents. The IVHM Project made major strides in vehicle health management in the area of advanced sensors and sensor systems, data mining, advanced diagnostic/prognostics algorithms, software health management, verification and validation, and IVHM open architecture.

In particular, development of a vehicle level reasoning system was initiated under IVHM and continues into the System-wide Safety Assurance Technologies program [78-79]. This activity is summarized in Figure 5.1 and involves:

1.  Generic platform reasoner to provide a common code base for one-time certification

2.  Clear separation between components of the vehicle level reasoner: data manipulation and state extraction monitors (evidence generation), the reference model that encodes aircraft specific configuration, and the reasoning engine (evidence interpretation)

3.  Information and data exchange using standard messaging protocols. This includes information from the Flight Data Acquisition Management System Digital Flight Data Acquisition Unit (FDAMS DFADU)

4.  A reasoner containing a deterministic set of operators and reusable computational blocks. These are distributed to manage scalability and computational tractability

5.  Monitoring of data to capture fault evidence without exposing potentially proprietary information.

6.  An offline data mining process for continual learning and update of the system reference model for the vehicle.
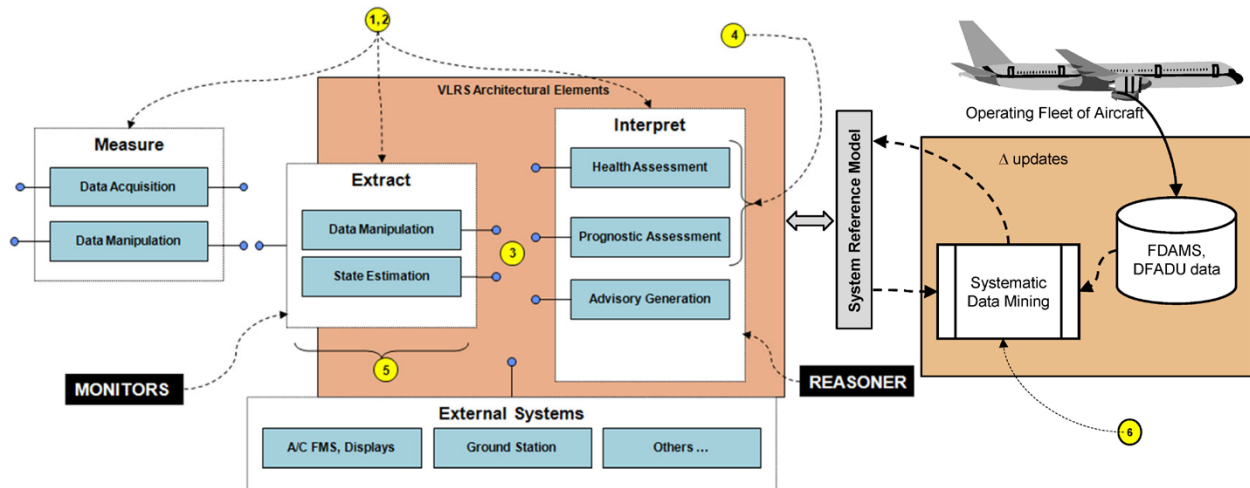
Figure 5.1.—Technical approach of the Vehicle Integrated Prognostic Reasoner [78]

This vehicle level reasoning system is an example of technologies supported by NASA related to health monitoring systems. This vehicle level reasoner is also an example of a framework which might be used in an overall Vehicle Health Assurance approach. Examples of IVHM systems also exist outside of aeronautics such as space craft based systems also including a system level reasoners [80].

The impact of IVHM development is now being seen in industry with anomaly detection tools (Southwest Airline [81]) to improve the safety of current operations, open source algorithms and datasets on a public website (DASHLink) [82], collaborations with industry/other government agencies (OGA), flight experiments, world-record development of high temperature sensors and electronics, and adoption of specific IVHM technologies in aircraft subsystems.

Some examples of this impact are: 1) Vehicle level reasoning developments that have influenced the design of the Central Maintenance Computer of the 787, Embraer, and other major jets; 2) Transfer of the Automation Design and Evaluation Prototyping Tool (ADEPT) [83] Software to Gulfstream is being used to help design and analyze new concepts for controlling systems functions; pilot fatigue risk management studies are underway at easyJet and ONERA; and 3) Engine testing collaboration was formed after the IVHM program leading to researchers at NASA, Pratt & Whitney and the Air Force to test IVHM engine technology in a transport scale engine [84].

The ability to safely incorporate technological advances and operational improvements in a rigorous and cost- and time-effective manner is essential for enabling the Next Generation Air Transportation System. Already, the complexity of current-day flight-critical systems poses significant challenges to safety assurance. To address these needs, the NASA SSAT Project is developing new paradigms for providing high levels of confidence in safety assurance. In particular, an integral part of the safety assurance process is verification and validation, which can be very costly and in some cases prohibit novel operations and technologies. Moreover,

errors can occur even after verification and validation have been completed on a system because of the large number of interactions that the system has with other systems. To enable verification and validation of these complex technological and operational developments, the NASA SSAT Project is developing new tools and technologies for manufacturers and certifiers to use to improve safety assurance for current and future air transportation. These tools and technologies will facilitate the implementation of the Concept of Operations described in this document, and will be transitioned to the FAA, the Joint Planning and Development Office, industry, academia, and other partners to benefit the public.

Under its Atmospheric Environment Safety Technologies (AEST) Project, NASA is investigating sources of risk and providing safety technology needed to help ensure safe flight in and around atmospheric hazards. Existing NASA vehicle health management capabilities can potentially help in the identification and mitigation of such hazards. For example, real-time monitoring of vehicle health can potentially detect and quantify the severity of environmental hazards such as aircraft/engine icing and volcanic ash ingestion. This information can in turn be used for real-time on-board mitigation functions (e.g., flight controls or cockpit annunciations), or used to generate post-flight inspection/maintenance recommendations to address any identified environmental-induced damage. Under the VSST Project, ongoing work in the MVS and ASC Technical Challenge areas will collaborate with the AEST Project on iced engine detection and control mitigation actions.

Other work involving NASA participation has concentrated on the use of digital systems in aircraft. Digital systems have used Hardware-In-the-Loop (HIL) since 1976 [85]. The technique combines simulation/emulation software with embedded hardware to achieve increased levels of model fidelity that includes real world effects. More recently, HIL has been applied to Unmanned Aerial Vehicles (UAVs). HIL has been used to validate the hardware and the software for a UAV autopilot based on the nonlinear control models [86-87]. HIL has also been implemented to test intelligent agents that would allow UAVs to operate in civilian airspace [88]. The use of the same embedded boards for development and implementation enables HIL capabilities or Aircraft-In-the-Loop (AIL). NASA has been using AIL techniques since the testing of the experimental X-29 airplane [89-90]. The NASA developed an F-18 Iron Bird facility at the NASA Dryden Research Center that provides both HIL and AIL simulation capabilities on a F-18 aircraft with hydraulically operated horizontal stabilizer, rudder, and ailerons [91]. To reduce risk during flight tests NASA has utilized AIL techniques during pre-flight tests on the Hyper-X 43 experimental hypersonic vehicle [92-93]. NASA also intends to perform AIL testing of the Global Hawk Unmanned aircraft.

The concept for Aircraft in the Loop testing of the onboard IVHM system is very simple: couple onboard SHM system and the external nondestructive testing (NDE) equipment together and allow sharing of data (Figure 5.2). External stimulus, such as loads, acoustics, heat sources, laser induced acoustics, etc., can be used to excite the structure so that they can be measured by onboard sensors. External NDE techniques can then be compared with the internal IVHM sensors to give improved results. Information from external systems can be transferred back to the internal system to increase situational awareness of the aircraft.

The U.S. Air Force is moving toward this concept and considering the feasibility of creating a digital twin for new aircraft. The foundation of the digital twin will be a high fidelity structural representation of the entire aircraft [94-95]. The concept is to create a digital model of an entire aircraft that can be used to virtually fly missions before the vehicle is put into service. After a vehicle is put into service, the model for each vehicle is continuously updated with monitoring data from each mission. The decision on whether an aircraft structure would need to be repaired before its next deployment would come from the current state risk analysis of the operational model, i.e., the digital twin [96]. This model will be capable of taking inputs of aerodynamic loads from either actual or forecasted usage and determining the stresses, strains, temperatures, and other environmental states in the structure. This information will be used to drive damage progression models that are tightly coupled to the structural model [94-95].

A unique digital model is created for each aircraft in a fleet, so that condition-based maintenance can be performed to inspect specific aircraft or aircraft components which experience more severe use, while deferring maintenance on those aircraft or components that experience more benign use. While each aircraft has a unique digital model, some data is shared in order to determine if any anomalies exist or to better inform each model. For example, it will not be necessary to equip each aircraft with sensors for monitoring loads in every critical location since sharing information across models can help to better inform all the models across multiple locations.
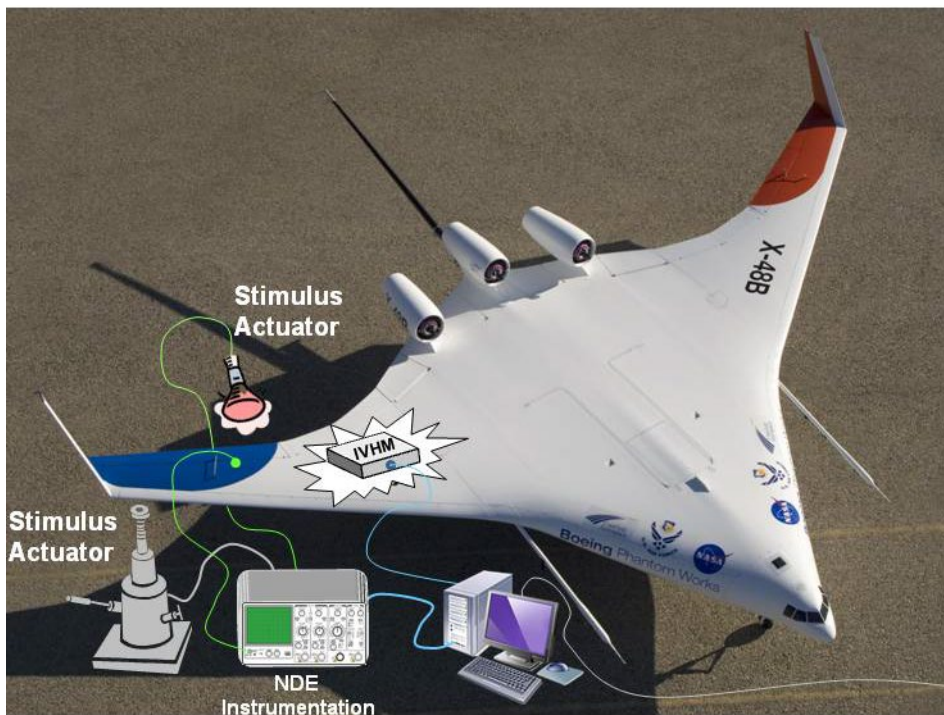


Figure 5.2.—Concept for Aircraft in the Loop testing of the onboard Integrated Vehicle Health Management (IVHM) system.

In addition to the digital twin concept being developed within the U.S. Air Force, the other DoD agencies and the U.S. Coast Guard are developing some type of structural health monitoring plan for improved fleet management. This includes the Joint Strike Fighter that targets the use of condition based maintenance and a prognostics health management system across multiple components and subsystems. The approach takes into account the logistics chain with notifications of the need for maintenance to allow parts to be on-hand [97, 98]. NASA has incorporated the digital twin concept into the draft "Modeling, Simulation, Information Technology and Processing Roadmap" for [99] and "Materials, Structures, Mechanical Systems, and Manufacturing Roadmap" [100]. NASA is also interacting with the Air Force in this Digital Twin concept, and will aim to take lessons learned from the Joint Strike Fighter program.

NASA has invested significantly in a range of technologies that affect vehicle level system safety and health. Examples include advanced material systems and integrated health management technologies. These and other investments are beginning to see implementation, but the overall state of Integrated Vehicle Health Assurance is at a low level of maturity.

## 5.2    NASA Airframe Contributions and Capabilities

### 5.2.1    NASA Historical Airframe Contributions

#### 5.2.1.1    Damage Tolerance/Materials

In the early 1950s, several fatal accidents involving De Havilland Comet aircraft shocked the aviation community. The root cause for these accidents was determined to be fatigue cracks growth, a damage mode that had not been considered when designing the aircraft structure. At the same time, George Irwin at the Naval Research Laboratory was developing new concepts in the field of fracture mechanics that could be directly applied to engineering structural materials. [101]. By applying fracture mechanics concepts to the study of crack growth, the concept of damage tolerance for engineering structures was formed. Throughout the 1950s and 1960s, NASA played a critical role in developing the principals of damage tolerance for aero structures. Here, the structure is considered to be damage tolerant if a maintenance program can be implemented that will result in the detection and repair of accidental damage and fatigue crack growth before such damage results in the residual strength being less than that required during operation. By the early 1970s most aircraft structures were designed and managed using damage tolerance principals. Inspection intervals are set based on life estimates, the number of cycles or missions for an assumed minimum sized crack to grow to a critical size. A critical development in determine safe inspection criteria was the development of software codes which utilized fatigue crack growth rate data to determine life and inspection cycles. The first commercially successful code was developed by NASA (NASGRO), although this code was first intended to be used for spacecraft, it was found to be of great value in damage tolerance criteria for aircraft as well [102]. The codes in use today with aircraft manufacturers and the DoD (i.e., AFGRO) are largely derived from the NASGRO code.

April 28, 1988, marked another significant event in the application of damage tolerance principals to aircraft structures. On this date Aloha Airlines flight 243 experienced an explosive decompression in flight. The investigation determined that multisite damage resulted in the linking of small fatigue cracks to create a critical damage event. NASA and the FAA created a joint program to study this damage and to better understand the damage processes present in aircraft structures as a vehicle ages. As a result of this program, new knowledge in the areas of corrosion, corrosion fatigue, wide spread fatigue damage and crack closure were applied to damage tolerance philosophies to mature the engineering practices and improve safety margins [103].

For the past two decades, the primary focus of study in the area has been to reduce the uncertainties associated with damage propagation in aero structures. This work aims to insure greater safety and enable reduced aircraft weight as well as developing damage tolerance approaches to emerging material systems that are highly anisotropic, and therefore are difficult to rationalize in the continuum approaches used in current damage tolerance design. Lightweight metallic materials, such as aluminum-lithium and titanium alloys, and composite materials are highly desirable for use in aircraft structures for weight savings. However, damage initiation and evolution are much more difficult to predict and model than in materials that have historically been used in aircraft structures. As such, NASA has contributed greatly to understanding damage processes in these emerging materials systems and much of this work has enabled the inclusion of new materials in military and civilian aircraft [104].

### 5.2.1.2    Inspection and Monitoring

Over the years, NASA has contributed to the SOA in airframe inspection. For example, NASA developed computational, experimental, and nondestructive evaluation methods to understand the structural failure that resulted in the loss of the vertical tail of an Airbus A300 flying as American Airlines flight 587 on November 12, 2001. This effort supported the National Transportation Safety Board's investigation of the accident and was the first time that progressive failure analyses were used to explain the failure of a flight structure made of composite materials. Various other techniques including thermography, ultrasonic inspection, and eddy current inspection have been developed to address the needs of the current aircraft fleet [105]. As a result of these contributions, technology has been transferred to private industry for commercial product development. For example, Krautkramer Branson, now a division of General Electric Measurement and Control, licensed a self-nulling eddy current probe developed by NASA. The development of fiber optic technology with corresponding data sampling approaches has been on-going. These fiber optic systems have been demonstrated in-flight on the vehicles such as the NASA Ikhana UAV [106] with a broader range sensor coverage than available with standard wire technology. Another notable application includes the integration of wireless impact monitoring sensors on the wing leading edge of the Space Shuttle to monitor for structural damage [107].

### 5.2.2 NASA Airframe Capabilities

#### 5.2.2.1 Materials for Airframe Health Management

NASA is developing several material concepts that are intended to intrinsically improve health management through improved material and structural durability as well as developing materials designed to enable structural health monitoring. Of these material concepts, several were envisioned at NASA and have been submitted through the patent process [108-110]. These materials have been demonstrated through proof-of-concept level and are being evaluated for specific damage processes for legacy and next generation aircraft and concepts for component replacement, repair and design of new material systems are being developed.

##### 5.2.2.1.1 Healing Materials

Several healing material concepts have been proposed over the past 10 years. A majority of these concepts encapsulate a monomer within a capsule or hollow tube within a polymer matrix composite [111]. When propagating damage results in rupture of the capsule, the monomer is released and reacts with catalyst that is distributed throughout the matrix. While this concept is extremely promising, the concept has proven difficult to implement in aero structures due to temperature limitations and for the fact that it only addresses matrix cracking in polymer matrix composites. The self-healing composite concept currently being investigated by NASA is a thermoplastic resin that can be manufactured as a fiber reinforced composite, which has been shown to heal damage induced from impact events. Here, damage is healed and the material is returned to near initial state prior to damage progression. As impact damage is of particular concern for new aircraft containing primary composite structure, the inclusion of these materials in components prone to impact events could result in a more damage resistant airframe.

Fatigue crack growth is the critical damage process in metallic airframe components. Although new aircraft designs are utilizing increased composite content, the current commercial aircraft fleet is predominantly comprised of metallic primary structure and the majority of the fleet for the next 25 years is expected to be dominated by vehicles comprised mostly of metallic primary components. Consequently, the development of a healing concept for improved durability of metallic components is also desirable. Here, a thin film concept has been developed where the healing agent can be activated to flow into an existing fatigue crack resulting in the mitigation of damage propagation. The thin film can be applied to the entire surface of components or near "hot spots" prone to damage. Since it is a thin film application, this concept can be used for new or replacement components or applied to existing components that may be found to experience damage. Since the film is applied to the structural material, the technology should be easily inserted into service and should not require the extensive certification that is necessary for new structural materials.

##### 5.2.2.1.2 Sensory Materials

The ability to monitor damage in a structural material using NDE sensors is limited by the physical interaction of the sensor with the material. Material selection and damage detection are usually considered separately. However, sensory material concepts attempt to integrate systems,

which facilitate the measurement of damage within a structural material. The concept currently being examined by NASA is to embed particles within a metal matrix which undergo a phase transformation upon being strained. This concept utilizes existing NDE sensors to monitor damage in real time using on-board sensors (acoustic emission) and more accurate and detailed examination can be performed using Eddy current probes to measure the size and location of the damage. This two-fold approach has the potential to insure that all damage will be found and no structural damage will go undetected, even in locations that are very difficult to access and inspect using current methods.

### 5.2.2.2    Inspection Techniques and Sensors for Airframe Health Management

Currently, NASA is furthering the SOA through development of analysis tools for collected data. Advanced thermographic data reduction techniques have been demonstrated for defect sizing and material aging. Analysis tools for guided wave imaging techniques are under development to reduce collected data to quantifiable results suitable for airframe health prognosis. NASA has made significant contributions to the field of sensor technologies for airframe health monitoring. As part of the Aviation Safety program and as detailed below, NASA has developed fiber optic sensor technology that, coupled with NASA developed interrogation techniques, permits distributed measurements for evaluation of airframe state. NASA has also developed in this work distributed strain sensing for the purpose of detecting off-nominal strain fields in airframe components. Causes for off-nominal strain fields are, for example, fastener failure, structural component failure, and excessive loading. In addition, lightning detection methods using fiber optic cables have been demonstrated. Additionally, NASA developed carbon nanotube (CNT) sensors as a low weight, microminiature sensing technology suitable for integration into structures [112]. Further highlights of these capabilities are described below.

### 5.2.2.2.1    SAW Strain Sensors

Surface Acoustic Wave (SAW) devices are being developed for passive wireless strain sensors. These sensors would not require batteries and are capable of working in harsh environments. SAW devices have been demonstrated to work in environments from cryogenic to high temperatures, and are immune to vibration, radiation, and pressure changes [113]. SAW devices have proven to be extremely sensitive to strain. The Decadal Survey of Civil Aeronautics: Foundation for the Future, identified IVHM as the top NASA and national priority within the area of materials and structures [114]. The survey also identified IVHM systems that warrant attention over the next decade such as "locally self-powered, wireless microelectromechanical sensors of various types tiny enough that very large numbers of sensors become practical." Strain gages have been used to monitor load conditions and fatigue, and to detect cracks in airframes [115-116].

Surface Acoustic Wave (SAW) devices have proven to be extremely sensitive to strain. Crack detection sensitivity of 0.01 mm has been demonstrated using these devices [117]. For these, and many other reasons [118], standard strain gages have been used to detect cracks in aircraft [115]. For example, a system capable of 1 microstrain ($\mu\varepsilon$) resolution has been demonstrated for crack monitoring both before and after repairs [119]. Therefore, 1 $\mu\varepsilon$ was established a good sensitivity

target for SAW strain sensors. The current SOA for wireless sensing of strain is MicroStrain Inc.'s SG-Link wireless strain gauges with a sensitivity of $\pm$ 2.5 με, weight of 46g, and a volume of 73.89 cm$^3$ [120]. The SAW devices we propose to investigate shall be at least an order of magnitude better sensitivity ($\pm$ 0.25 με), volume (7.39 cm3), and mass (4.6g).

### 5.2.2.2.2    Fiber Optic Strain Sensors (FOSS)

Strain and temperature sensing fiber has long-term applications for IVHM research. Fiber sensors can be active or passive interrogation devices. Fiber Bragg grating technology is NASA's primary focus in this area, however Rayleigh and Raman scattering techniques could also be used in the same fiber. The primary benefit from this technology is that several hundred gratings within one fiber spanning many meters can be demodulated for damage detection and monitoring at multiple locations [121-122]. Fiber can also be embedded into the structure (e.g. even metals [123]) or temporarily attached using an adhesive tape. The sensor information is generated using laser light and processed with photodiodes through electronics. This information can be processed in situ or compressed and sent through telemetry to storage or processing. Using this technology a large number of strain sensors with low power consumption and weight per sensor can be used to collect strain data at one or several fixed locations on an aerospace vehicle, analogous to an animal spinal column with fiber nerves.

Frequency domain scanning of Bragg gratings allow high sensor density with lower sampling rate compared to time domain sensing. Advances in laser technology are linked to increases in the sampling rate. Luna Innovations, Inc. has licensed the patent for this technology from NASA and continues to develop laser technology and signal processing techniques for commercial applications [122]. Luna's work continues to increase the system sampling rate, along with that of NASA Dryden. NASA is exploring new ways to use this technology for IVHM using system modeling and expanded applications such as thermography [124].

Fiber optic Bragg grating devices are used as distributed strain and temperature sensors inside single mode fiber. Hundreds up to thousands of sensors can be written in the fiber as individual sensors [125]. These sensors are immune to electromagnetic noise, corrosion, can be used in harsh environments, and do not pose an ignition source so they can be used in potentially explosive environments [126]. This is a drastic improvement over conventional wired strain gage systems. The fiber can be interrogated in-situ to collect structural information during and after flight. Temperatures have been measured at –269°C with a 600°C maximum calculated temperature [127].

## 5.3    NASA Avionics Contributions and Capabilities

### 5.3.1    NASA Historical Avionics Contributions

Broadly speaking NASA's recent contributions to health management for avionics systems is focused on completing the research and early development needed to enable the next generation of prognostics and diagnostics capabilities for the safety critical areas discussed in the Section 3.3. In many cases this work may ultimately allow industry to put systems in place that can

automatically spot the early onset of problems, predict time to failure, and help maintainers address issues long before they become safety critical.

### 5.3.2 NASA Avionics Capabilities

#### 5.3.2.1 NASA Capabilities in Electrical Wiring and Interconnect Systems (EWIS)

The Vehicle Systems Safety Technologies project currently funds research focused on developing advanced physics-based models and algorithms for detecting chafing to commonly used types of shielded impedance controlled aircraft cable (e.g., coax and twisted-shielded pair). While this type of cable is traditionally used to transmit bus or RF communication signals, twisted shielded pair cable in particular can also be used to distribute power (although this is not current practice, with the move towards composite materials it may become better practice to transmit power and ground signals together). The contributions from this approach fill gaps in the SOA industry capabilities summarized above. In addition, NASA's research holds promise for resolving many of the technology barriers, listed below, currently preventing chafing fault detection in the field [128, 129].

- Changing impedance along the length of some cables causes large reflections that mask chafing fault signatures, especially in field environments.

- Prior knowledge of baseline measurements and how these baselines change over time in an operational environment is required for the nominal un-faulted cable, which can then change over time in an operational environment.

- Expert knowledge is needed to interpret the measured TDR fault signatures, which are often buried in noise. While this knowledge can sometimes be automated using data driven supervised machine learning methods, it does not stem from the underlying physics of the problem.

- Fault detection signal processing is usually based on ad-hoc methods such as classical correlation (matched filter) methods that do not correctly account for frequency attenuation with cable length, or the fact that a single fault produces multiple reflection "signatures" within a single TDR measurement.

- Limited ability to map the fault reflection "signature" back to the actual fault size and fault location to quantify the measurement uncertainty —mostly this is because the true velocity of propagation for any particular cable is unknown ahead of time.

The model-based optimal fault detection algorithms, currently under development in VSST, use the measured time or frequency data to automatically estimate the model parameters, which include the physical fault location and size, and quantify error in a Bayesian probabilistic framework (including velocity of propagation). Under this paradigm, baseline measurements are not necessary and users no longer need to interpret raw TDR time signatures, since the model provides these capabilities. Furthermore, the rigorous physics-based approach to fault detection in a single cable enables the characterization of the best possible fault detection trade-space that

answers the question: *how far away and how small can the fault be detected for a given cable?* And answering that question in the context of physics, as opposed to field studies (which are important but also difficult to control, expensive, and time consuming), leads naturally leads to better cable and wiring system design principles. These capabilities all make steps towards enabling important aspects of condition based wiring maintenance with applications to commercial, general, and military aviation (not to mention a wide array of non-aerospace related fields).

### 5.3.2.2 NASA Capabilities for Other Avionics Health Monitoring Systems

The System-wide Safety Assurance Technologies (SSAT) project funds the development of modeling methods and algorithms with wide applicability to the prognostics and diagnostics of electronic and mechanical system issues in aircraft, including all of the related avionics subsystem components discussed previously (see Section 3.3.2 Avionics Emerging Factors). The algorithms are also evaluated on specific relevant test platforms and compared for performance through NASA Ames Research Center's Advanced Diagnostics and Prognostics Testbeds (ADAPT) lab [130]. Particular examples include the important contributions to capacitor, electro-mechanical actuator, and battery health management summarized in the section above, and detailed in the references [19, 131].

Notice the complementary nature of research efforts between these two Aviation Safety Program projects: VSST funds research into health management for a specific vehicle system that affects almost all other electronic systems (wiring), while SSAT funds the development of broad methods and algorithms that can be applied to a large variety of electrical and mechanical systems, and evaluates them for important specific subsystems and components. This dual approach optimizes coverage of the most important issues in avionics health management.

## 5.4 NASA Propulsion Contributions and Capabilities

### 5.4.1 NASA Historical Propulsion Contributions

Over the years NASA, working in collaboration with external partners, has made significant contributions to the SOA in aircraft engine health management. NASA contributions in the areas of gas path diagnostics, mechanical component diagnostics, structural lifing, and sensing technologies are further discussed below.

#### 5.4.1.1 Inspection and Monitoring

#### 5.4.1.1.1 Mechanical Component Health Monitoring

Over the years, NASA has made numerous contributions in the field of mechanical component health monitoring, most notably in support of rotorcraft gear and transmission monitoring for Health and Usage Monitoring Systems (HUMS) applications. Much of this work has been conducted in collaboration with the U.S. Army. This includes extensive research in gear and gearbox vibration diagnostics [132], as well as transmission system [133] diagnostics. Additionally, the NASA has also evaluated and reported on the benefits on integrating vibration and oil debris based techniques for improved damage detection of mechanical component faults

[134]. Such information fusion techniques hold much promise for improving the performance of future engine health management systems.

### 5.4.1.1.2     Life Prediction of Propulsion Structures

Understanding and adhering to the safe operating life of critical life limited parts is critical to assuring aircraft propulsion system safety. However, accurate life prediction is unique and challenging in this application area due to the high stress loads, repeated operating cycles, and the high temperatures encountered. Over the years, NASA has made significant contributions in area of aircraft engine life prediction. This includes pioneering work in the field of bearing lifing [135] and gas turbine engine high temperature alloys [136]. This NASA research continues to play a fundamental role in establishing the way aircraft engine life limited parts are operated and managed today.

### 5.4.1.2     Gas Path Health Monitoring

NASA has been involved in the field of aircraft engine gas path health monitoring for several decades. This involvement initiated in the late 1970s under a NASA led effort on aircraft engine performance retention, including work in engine diagnostics. In 1981, NASA hosted an industry-wide workshop on Aircraft Engine Diagnostics that highlighted many of the foundational gas path health monitoring approaches that are still in use today [137]. The NASA aircraft engine performance retention program also consisted of contracted efforts with engine manufactures to document aircraft engine performance deterioration trends based on historical airline data [138,139]. The ensuing reports established an understanding and a means to forecast gas path module performance deterioration trends. In the 1980s, NASA partnered with industry and the DOD on the Performance Seeking Control Technology Program. This entailed the implementation of on-board analytical engine models with an associated tracking filter for tuning the model to match the performance of the engine based on engine sensor measurements. Such on-board models have several applications including engine controls, performance trend monitoring and diagnostics. More recently, under the Aviation Safety Program, NASA has worked with industry to enhance on-board model technology by combining analytical and empirical modeling techniques [140].

### 5.4.2     NASA Propulsion Capabilities

### 5.4.2.1     Materials for Propulsion Health Management

Current and emerging commercial aircraft are utilizing advanced materials in propulsion components including advanced Ni-base superalloys for turbine disks [141] and polymer matrix composites for engine structures [142-144]. Work within the VSST project addresses potential safety issues for recently implemented technologies as well as robust design for future emerging technologies. New materials have been introduced in propulsion systems for improved performance; however, these modifications introduce new potential safety concerns particularly under long term use when components in operational environments often experience aging-related issues.

### 5.4.2.1.1 Advanced Ni-base Superalloy Disks

A turbine disk is a fracture critical structural engine component, as a failure usually results in a loss of engine, considerable airframe damage, and the possibility of loss of the aircraft. High strength, high temperature disk alloys are susceptible to surface processing defects that have been known to cause failures [145]. Twenty five percent of FAA Airworthiness Directives publicly issued in the first 6 months of 2012 have been associated with enhanced inspections to detect compressor and turbine disk cracking, in order to prevent uncontainable disk failures. This cracking is usually at machined surface features and notches. Advanced Ni-base superalloys, designed to withstand higher temperatures to improve engine efficiency, are being utilized in compressor and turbine disks in current and emerging commercial aircraft [141]. While the durability of these material systems was assessed during the material development and engine certification, safety issues can emerge as the new technologies accumulate time in service.

Long term operation of engines at higher temperatures, with the aggressive environments and engine contaminants, may result in previously unobserved oxidation, corrosion and near-surface changes to the microstructure, which can significantly degrade mechanical properties [146-149]. The effect of these near surface changes on disk life must be evaluated. Stable protective coatings are being developed for long term service at temperatures up to 760°C to protect disks from corrosion and oxidation. Corrosion could lead to premature fatigue crack initiation and the failure of a turbine disk prior to the anticipated retirement of the component. A detailed characterization and modeling of the near-surface layer after current and advanced surface processing, including application of coatings, is needed for more accurate life prediction. Models will be developed that can relate environments, coatings, superalloys, and cycling conditions, that could later be related to actual engine environmental conditions for various engines and flight cycles. The long term goal will be to have accurate life prediction capabilities for advanced Ni-base superalloy disks.

### 5.4.2.1.2 Composite Materials for Engine Structures

Composite materials are beginning to be used for fan cases and other engine primary structures [142-144]. There is limited service experience with composite components, and failure mechanisms are not well understood [150-152]. Technologies will be developed to provide a more robust assessment of safety for these composite engine structures, for both current and future applications. Potential effects of material aging in simulated engine environments and impact damage from various sources (bird strike, hail, and foreign object debris (FOD)) will be investigated to assess safety over the full life cycle of an engine. New test methods, which accurately simulate impact conditions for an in-service failure, are being developed to evaluate existing and emerging material concepts. Cooperative work with the FAA and universities is being conducted to develop more accurate computational impact models that better predict the effects of aging on both in-service and processing induced flaws. New nondestructive detection techniques are being developed that allow a much higher quality of flaw detection and visualization. These combined efforts will lead to a higher level of confidence in assessing the structural integrity of proposed and in-service composite engine structures, resulting in greater safety.

## 5.4.2.2 Gas Path Health Management

An emerging approach in the field of aircraft engine design is the inclusion of on-board self-tuning engine models for control and health management applications. This technology, which has been enabled by advances in flight processing capabilities, consists of an aerothermal engine model and an associated tracking filter. The tracking filter, typically based on a Kalman filter, is designed to process engine gas path sensor measurements to estimate and adjust a vector of model tuning parameters reflective of engine performance. This automated tuning parameter adjustment allows the engine model to "self-tune" to match the performance level of the actual engine, and produce estimates of measured and unmeasured engine outputs that can be applied for performance trend monitoring and gas path diagnostic purposes. Additionally, the model-produced parameter estimates can also be applied for controls and prognostic applications.

A challenge in designing accurate self-tuning engine model technology is the inherent underdetermined nature of the estimation problem. Typically, there are more unknown parameters than available sensor measurements. Recently, NASA has developed a systematic approach for selecting the tuning parameters applied within self-tuning engine models [153]. This analytical technique, designed to minimize the model's estimation error, provides system designers a tool that enables them to optimize the tracking filter design for their given applications. It also enables them to assess design decisions, such as the estimation accuracy improvement that could be gained by adding additional sensors. Application of this approach has been shown to yield a significant improvement in model estimation accuracy compared to conventional design approaches.

In addition to improving self-tuning model accuracy, NASA has also recently worked to develop a model-based gas path health management architecture designed to process streaming, continuous engine data [154]. This architecture, like conventional gas path analysis based on snapshot measurement data, provides performance trend monitoring and gas path fault diagnostic functionality. However, unlike conventional approaches, which are primarily performed off-board based on a limited number of snapshot measurements collected at fixed operating points during each flight, the processing of streaming data approach collects data over the engine's entire operating profile including transient conditions. This new design, which enables improved diagnosis of incipient fault conditions with reduced diagnostic latency, is suitable for either on-board or off-board implementation. Implemented on-board, the architecture provides real-time continuous health monitoring functionality. Alternatively, as data acquisition, transmission, and archival restrictions lessen in the future, the architecture is suitable for processing streaming full-flight engine data available off-board.

To facilitate the development and evaluation of propulsion controls and health management technology, NASA has developed transient aero-thermal engine models, which are publicly available through the NASA Glenn Software Catalog [155,156]. These models, referred to as the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) and Commercial Modular Aero-Propulsion System Simulation 40,000 pound thrust (C-MAPSS40k), are representative of commercial aircraft turbofan engine designs. They include a realistic closed-

loop control system, full-envelope transient simulation capabilities, and the ability to simulate gas path system faults. These models enable the initial development and comparison of gas path diagnostic methods by members of the engine health management community.

### 5.4.2.3    Sensors for Propulsion Health Management

In order for future aerospace propulsion systems to meet the increasing requirements for increased safety, decreased maintenance, and improved capability, propulsion system design and operation must become more intelligent [157-159]. NASA is a leader in Microsystems and harsh environment-based instrumentation, sensors, and electronics with an existing long-standing program in Microsystems and sensors for harsh environments and safety applications. The overall program has won four R&D 100 Awards (one of 100 Most Significant Inventions/Products of the Year) in the last 15 years, one Nano 50 Award (one of 50 technologies to impact nanotechnology), a NASA Top Discovery Story in 2007, has been nominated for NASA Invention of the Year in 2009, and has received a range of international recognitions. Overall, there are a range of technologies where NASA is unique and world-leading.

In particular for propulsion system health monitoring, NASA has been active in developing sensor technologies to detect, locate, and identify damage not only by passively sensing their surroundings but also actively interrogating it. The sensor development follows the principle of considering the complete sensor system including the overall need to reduce sensor size and weight, the need to improve sensor reliability, and ultimately to reduce sensor false alarm rate. This implies the development of sensors and electronics, with associated packaging, that will be able to operate under the harsh environments present in an engine.

In order to monitor the vast range of components associated with an engine, an array of sensor technologies are of interest [27, 157]. Figure 5.3 shows the relationship between sensed parameters and relevant engine conditions of interest for control/health monitoring applications. Among these, temperature, flow and pressure associated with gas path health monitoring are of interest, and emissions have correlation to the state of the combustor via combustion process and other engine heath conditions. NASA has led the development of a range of technologies addressing various aspects of the measurements noted in Figure 5.3. This development has often been in collaboration with industry, and motivated by an understanding of the instrumentation needs for engine systems [160]. The following briefly gives some notable examples; further descriptions of the technology and safety applications can be found in references [161,162].

**Propulsion Control & Health Management Technology**

| Inlet | Fan / Comp. | Combustor | Turbine | Nozzle |
|---|---|---|---|---|
| • FOD and hot gas ingestion detection<br>• Ice accretion detection<br>• Inlet shock control | • Stability margin management<br>• Active stall control<br>• Active flow control<br>• Life management<br>• Clearance control<br>• High cycle fatigue detection | • Combustion instability control<br>• Emissions minimizing control<br>• Burner pattern factor control | • Active turbine tip clearance control<br>• Life management<br>• Active cooling control | • Domestic object damage detection<br>• Blade erosion and rub detection<br>• Afterburner light-off detection |

**Sensed Parameters**

| Inlet | Fan / Comp. | Combustor | Turbine | Nozzle |
|---|---|---|---|---|
| • Inlet debris<br>• Inlet shock position<br>• Pressure & temperature | • Stall precursors<br>• Flow separation<br>• Stress, strain<br>• Tip clearance<br>• Blade time of arrival, bending, flutter<br>• Vibration<br>• Pressure & temperature | • Combustion instabilities<br>• Emissions<br>• Burner pattern factor<br>• Pressure & temperature | • Blade tip to casing clearance<br>• Turbine inlet temperature<br>• Blade/vane temperature<br>• Vibration<br>• Stress/strain | • Exhaust debris<br>• Pressure & temperature |

Figure 5.3.—Propulsion control and health monitoring technologies and associated sense parameters [157].

### 5.4.2.3.1 Self Diagnostic Accelerometer

Accelerometers are commonly utilized for structural health monitoring of both aircraft and spacecraft engines [161-163]. Accelerometers generally monitor machine health by monitoring vibration measurements in a particular frequency band for exceedance of acceptable vibration magnitudes and rotor-out-of-balance conditions. Real-time sensor validation is necessary to prevent a vehicle controller, or facility safety system, from making critical decisions, such as one to shut down an engine, on the basis of anomalous sensor data. The Self Diagnostic Accelerometer is an electronic diagnostic system that monitors the accelerometer sensor enabling a smart sensor system. This system identifies changes in temperature, sensor loosening, and sensor structural or electrical damage. This technology provides a real time method of sensor validation that can be utilized as part of a propulsion structural health management system to improve overall reliability of engine health assessment.

### 5.4.2.3.2 Microwave Blade Tip Clearance Sensor

Microwave sensor technology has been developed as part of a NASA SBIR program as a means of making non-contact structural health measurements in engine hot sections [161]. High Cycle Fatigue (HCF) of rotating components, specifically blades, is a common failure mode and is due to high vibration levels of the rotating components and blades [157, 164-165]. This microwave blade tip clearance sensor can be used in the harsh environment of a turbine engine resulting in

the capability to make in-situ health measurements of the engine's rotating components, specifically the High Pressure Turbine and High Pressure Compressor sections. This type of sensor is accurate, operates at extremely high temperatures, and is unaffected by contaminants that are present in engines. This technology can also be used to monitor blade growth and wear, and blade tip timing to monitor blade vibration and deflection. A general standard for this sensor type is in development [166].

### 5.4.2.3.3 High Temperature Fiber Optic Sensors

The high temperature fiber optic sensors aim to provide expanded sensor coverage of sensed parameters through the use of fiber optic technology for reliable measurement in hot sections of the engine. Optical devices are immune to the effects of electromagnetic interference and therefore do not need electrical insulation. This makes the sensors well suited to work in an electrically charged environment and in locations where electrical discharge may be an issue. Furthermore, the small diameter of the fiber permits easy embedding within structures and multiple sensors can be put on a single fiber and there is no need for separate power wires. The development of high temperature optical thermal focuses on optical fibers with Fiber Bragg Gratings (FBG) written into the fiber operable at temperatures up to 1000°C. A major point to note is that these sensors are based on the standard silicon based optical fibers, rather than specialized, less available high temperature fibers such as quartz.

### 5.4.2.3.4 Thin Film Physical Sensors

Thin films sensors including those for strain, temperature, heat flux and surface flow enable critical vehicle health monitoring and characterization of engine components. The use of sensors made of thin films has several advantages over wire or foil sensors. Thin film sensors do not require special machining of the components on which they are mounted, and, with thicknesses less than 10 μm, they are considerably thinner than wire or foils. Thin film sensors have a minimal impact on the physical characteristics of the supporting components. The need for sensors to operate in harsh environments is illustrated by the need for measurements in the turbine engine hot section. The degradation processes that occur in the harsh hot section environment are poorly characterized, which hinders development of more durable components, and since it is so difficult to model turbine blade temperatures, strains, etc., actual measurements are needed.

### 5.4.2.3.5 Emissions Sensor Array

The emissions that an engine produces are understood to be indicative of the state of the combustion process, reflective of other engine health parameters, and have direct effect on engine bleed air and the cabin environment. An array of sensors placed in the emissions stream close to the engine exit could provide information on the gases being emitted by the engine. However, there are very few sensors available that are able to measure the components of the emissions of an engine in-situ. NASA sponsored and collaborative work with academia and industry, as well as funding by the Navy, has concentrated on developing emissions sensors, and integrating these sensors into an array that can be placed at the engine exit [167-170]. The results of the Navy funding showed the viability of this approach to provide measurements comparable

to standard instrumentation. This application was for engine qualification, not directly for health monitoring.

### 5.4.2.3.6    High Temperature Smart Sensor Systems

Currently, for almost all sensors, actuators, or processing units installed on an engine for improved in-situ monitoring of the components, communication and power wires must follow. More sensor systems added to the aircraft increases the number of wires and the associated weight, complexity, and potential for unreliability. In general, "Wiring on an aircraft is complex, difficult to route, heavy and a key source of faults, which lead to delays and cancellations for passengers. Engineers thus try and minimize wiring as "every wire is a source of failure and every wire adds weight" [171]. Further, sensor reliability and integrity of data is often improved by local processing. Work is leading toward self-contained complete wireless sensor systems with integrated intelligence that can be applied like a postage stamp, without the need to rewire the systems ("Lick and Stick" technology). This High Temperature Smart Sensor System approach allows improved sensor data and increased capability to implement the system. It involves a complete system: sensors, signal processing, wireless communication, and power capabilities. Such technology is viable in silicon (Si) based electronics for near room temperature operations [167,168,172], but is a technical challenge for high temperature environments.

Beyond the high temperature sensor element technologies described above, development of components of the High Temperature Smart Sensor includes:

- Silicon carbide (SiC) electronics and packaging: NASA has been a world leader in the development of SiC electronics with a significant number of internationally recognized breakthroughs [173]. SiC has shown the potential of a meeting a range of engine application needs [174-176]. Operation of 500 °C has been demonstrated for thousands of hours enabling potential implementation in engine conditions for extended periods [162,177-178].

- High Temperature Wireless Communications (500 °C): NASA activities aim to use high temperature compatible materials to fabricate a complete wireless circuit [179]. Notable advancements include demonstration of wireless transmission at near 500 °C of position transducer data [180], and 500 °C transmission of pressure data both by wire and wirelessly [181].

- Power scavenging: Power scavenging using thermoelectrics or piezoelectrics [182,183] that take advantage of the energy already present within the engine have notable appeal for self-powered sensor systems. NASA has led development of a range of relevant thermoelectric based technologies (for 500 °C operation [184-187]).

The integration of sensors, electronics, power scavenging, and wireless communication components has been demonstrated at 300 °C [188]. This was considered a proving ground for technologies to allow 500 °C smart system operation.

### 5.4.2.4 Vehicle Integrated Propulsion Research (VIPR) Test Program

Vehicle Integrated Propulsion Research (VIPR), incubated in the IVHM project, is a means to test and evaluate emerging health management technologies on a commercial engine, incorporating new sensors directly on the engine, providing seeded fault scenarios, and evaluating advances in engine diagnostics. This step is critical in order for IVHM technologies to mature from lab work and simulations to TRL 6 demonstrations needed for industry acceptance. This work is in partnership with the Air Force, which has provided access to two F117 high bypass turbofan engines and time on operational planes for the ground-based, on-board engine tests. In these tests, the research engines are instrumented to achieve NASA and partner goals and mounted on a C-17 aircraft, though it is important to note that the planes are grounded and do not take flight.

A series of tests are planned with overall VSST objective of testing health management sensors, sensor systems and algorithms on a high bypass turbofan engine under the following conditions: (1) Normal engine operations; (2) Seeded mechanical faults; (3) Seeded gas path faults; and (4) Accelerated engine life degradation through volcanic ash ingestion testing

The first VIPR test took place in December 2011 at NASA Dryden Flight Center/Edwards Air Force Base as an on-wing ground test on a heavily instrumented Pratt & Whitney F117 high bypass turbofan engine. The following VSST test objectives were achieved, along with the partner objectives:

1. VSST emission sensor system test: a) test the sensor system's ability to detect a simulated oil leak and b) changes in sensor response with changing engine conditions

2. Self Diagnostic accelerometer feasibility test: demonstrate operability of self-diagnostic accelerometer in aircraft engine environment

3. Prepare microwave tip clearance sensor for on-board tests: perform electromagnetic interference (EMI/EMC) testing according to aircraft requirements

4. Validate Gas Path Diagnostics: test analytical model predictions of engine parameters in the presence of bleed valve faults (failed, full open; schedule bias)

Plans for further testing are in the formulation stage and are intended to include the majority of the technologies described above in Sections 4.3.2.1 and 4.3.2.2.

## 5.5 Summary of NASA Contributions and Capabilities

NASA has numerous past contributions and current capabilities that are relevant to Vehicle Health Assurance. Technologies targeting the health assurance of the vehicle include:

- Significant technology development related to detection, diagnosis, and prognosis within the IVHM project, and material and sensory development within the Aging Aircraft project.

- Significant development of subsystem technologies, with a framework available for an overall vehicle level system

- Airframe technologies and capabilities:
  - Sensory materials
  - Healing materials
  - Diagnostic and prognostic algorithms
  - Airframe sensor systems

- Avionics technologies and capabilities
  - Wiring diagnostics and modeling
  - Broad-based methods and algorithms
  - Testbeds for algorithm evaluation

- Propulsion technologies and capabilities
  - Advanced Ni-base Superalloy disks
  - Composite Materials for Engine Fan Containment
  - Gas path health management
  - Harsh environment sensor technology/smart sensor systems
  - On-engine testing and characterization

# 6.0 Vehicle Health Assurance Concept

## 6.1 Health Assurance System Scope and Overview

In today's environment, aircraft are assumed to perform reliably for extended periods between major inspections. Inspection intervals are based on set standards, not the condition of the individual vehicle. However, unique failures occur due to the service history of individual aircraft, or even potentially from aircraft-to-aircraft build variations. Moreover, these faults and failures are frequently not detected during inspections. Contributing factors include the following: 1) Inspections based on vehicle life assessments and engineering predictions determined at the beginning of aircraft service; 2) Faults and failures are detected utilizing external inspections, which are not always effective; 3) Use of on-board sensors is limited due to weight and harsh environment conditions; and 4) New technologies can create hazards not identified during development.

The VSST project, in recognizing the critical need to maintain a safe vehicle between major inspections, will develop and demonstrate new integrated health management and failure prevention technologies to assure the integrity of vehicle systems between major inspection intervals and maintain vehicle state awareness during flight. There are multiple approaches towards such an improved safety system.

## 6.2 Aviation Community Health Assurance System Approaches

Possible approaches to an Integrated Vehicle Health Assurance system, which includes Integrated Health Management, can be found in multiple documents. The Decadal Survey [189] states that:

"Integrated vehicle health management (IVHM) refers to monitoring, assessing, and predicting the health of aircraft materials and structures using networks of sophisticated onboard sensors. A fully integrated approach to IVHM relies on a multidisciplinary set of analysis, testing, and inspection tools, including miniaturized sensors and distributed electronics; sophisticated signal processing; data acquisition, integration, and database maintenance; artificial intelligence; damage science; and the mechanics of structures and their failure…IVHM benefits all classes of aircraft, in all speed regimes and phases of flight."

The National Aeronautics Research and Development Plan states that Fundamental Safety Challenges to Overcome include [190, pg. 31]:

- *Predicting, monitoring, and assessing the health of aircraft, at the material, subsystem, and component level, more efficiently and effectively.*

- *Applying novel sensing ... and estimation techniques to assist in stabilizing and maneuvering next-generation aircraft in response to safety issues ranging from ... on-board system failures, to unintended entry into unusual flight conditions and environmental hazards.*

- *Understanding and predicting system-wide safety concerns of … the vehicles as envisioned by NextGen, including the emergent effects of increased use of automation to enhance system efficiency and performance beyond current, human-based systems, through health monitoring of system-wide functions that are integrated across distributed ground, air, and space systems.*

Goal 1 of this plan is to "Develop technologies to reduce accidents and incidents through enhanced vehicle design, structure, and subsystems". It also states (pg. 32):

"Aircraft-level health-management systems, including sensors and analytical tools, will be developed that can identify problems before accidents occur. Research in health management requires not only monitoring and detecting, but also confident prognostics of latent potential failures before they occur. While health management is informed by the known accident and incident records of other vehicles, it is not restricted to those known conditions. The development of health management systems requires a deeper understanding of aging and degradation mechanisms in airframe and aircraft systems."

Joint Planning and Development Office (JPDO) *National Aviation Safety Strategic Plan* (*NASSP*) defines national goals, objectives, and strategies for aviation safety improvements. Vehicle health management systems also figure prominently within this National Aviation Safety Strategic Plan related to Goal 2: Safer Systems, Objective 2B – Provide safety enhancements for airborne systems [191, p. 6]:

"**Improve vehicle systems health management** through advanced monitoring systems and decision aids. These systems can monitor various aspects of systems health, both during flight and through post-flight analysis, including vehicle structures, propulsion systems, control system elements, and avionics hardware and software. To provide pilots, dispatchers and maintenance personnel with ready access to system health information, advanced aircraft monitoring systems will be developed that integrate sensor information. Integration of advanced monitoring systems will increase operators' timely and accurate understanding of system health, resulting in quicker identification of sub-system faults and failures and increased opportunity to successfully mitigate and prevent these failures. Enhanced decision aids will assist operators in preventing unacceptable safety risks from developing, enhancing operators' recognition and incorporation of complex factors in situation assessment and mitigative decision-making. To ensure an efficient response, certain system failures will precipitate automatic transition to alternate operating parameters, with backup procedures in the event of anomalous conditions. Executing this strategy will help to reduce the number of hazards encountered, enhance the understanding of off-nominal conditions, and reduce the response time in making optimal decisions, ultimately improving operator awareness and mitigative response to airborne events and hazards."

These and other external inputs, as well as existing NASA capabilities, suggest potential NASA approaches and concepts towards Vehicle Health Assurance. NASA's approach and Vehicle Health Assurance Concept will be discussed in the following sections.

## 6.3  NASA Recommendations

These approaches may be summarized to have a number of common themes and technology directions. The NASA viewpoint on future technology development may be summarized as follows:

- **NASA does not build vehicle systems. NASA's role in the Aviation Safety program is to do the research in order to provide a wide range of tools and approaches to enable those who do build, operate, and maintain aircraft to be able to achieve the next generation of vehicles with properties that enhance the nation's and public's safety.**

- **These tools must be practical to allow fleet wide implementation and potentially enable other benefits such as decreased emissions, increased performance, and decreased operating costs. Major impact within the next 5 years is a primary goal, and this impact is maximized by establishing a foundation for paradigm shifts in aviation technology.**

- **There is information available related to each vehicle now; there is often a challenge as what to do with that information. Further, if for no other reason than bandwidth restrictions, it is not feasible to continuously transmit all of the information to everyone who might need to know it. Systems that are more complex in their interface to the user and provide streams of unprocessed information will provide limited impact.**

- **Introduction of new technology must be aimed towards increasing system capability and safety, while minimizing complexity for the user, especially in cases of retrofitting vehicles.**

- **Local processing and hierarchal approaches are needed. In parallel to advances across the technology spectrum from the smart phone to automated parking, significant capabilities are achieved by highly complex intelligent systems with little impact on users.**

- **The fundamental concept for IVHAS is that increased intelligence of the vehicle will enable improved safety. This increased intelligence is established from the bottom up with integrated smart sensors and materials coupled with diagnostics and prognostics operating locally, feeding into smart nodes and subsystems, and finally across the vehicle. Overall, the intelligent system is enabled by integrated, local smart detection, diagnostics, and prognostics.**

**A safer vehicle is one that is constructed with materials that avoid safety issues, evaluates its own health and mitigates its own problems where appropriate, and provides information to flight and ground personnel in a simple, actionable way. Not all problems can be addressed given the resources of the MVS Technical Challenge. Rather, a range of tools will be targeted based on safety impact, and available NASA capabilities.**

While not an exhaustive list, based on previous NASA analysis and the above technical assessments, some recommended technical themes/directions include:

- Improve on-board sensor and detection systems for increased reliability and to provide better vehicle health information throughout continued use and system degradation, as well as during operation in unintended and unusual flight conditions and environmental hazards. This includes an emphasis on sensor technology that takes into account implementation issues.

- Improve methods for diagnosing aircraft health at the material, component, and subsystem levels, in addition to developing a complete system level approach that continuously incorporates vehicle usage and sensor data throughout the lifetime of the vehicle.

- Improve inspection and material design techniques that improve the capability to better understand the state of the vehicle both during major inspections, but also provide valuable information in between major inspections to identify potential safety issues.

- Integrate on-board flight information with ground inspection data into a unified assessment of vehicle health state to enable improved decision making and actionable knowledge to decrease inappropriate crew responses, and target maintenance activities.

- Identify the necessary technologies to ensure vehicle safety as the fleet ages and as new technologies are introduced into vehicle operation.

- Provide key information enabling the crew to better respond to Loss of Control situations and avoid inappropriate responses.

Thus, a primary objective of the Integrated Vehicle Health Assurance System Concept of Operations is to identify technologies to address the themes described above, as well methods to allow a pathway for their vehicle integration.

## 6.4    MVS Integrated Vehicle Health Assurance System (IVHAS) Approach

Vehicle-related failures are often the first factor in the sequence of events leading to safety incident and accidents. Precursors to vehicle faults and failures are frequently found during periodic inspections; however, many areas are inaccessible even during major inspections. This is illustrated in Figure 6.1. Damage and faults found and repaired during inspections results in a safe vehicle, as shown in Case 1. However, damage precursors in areas that are difficult to inspect may be missed, but could lead to a failure between inspections as shown in Case 2. Finally, damage can occur after a major inspection yet result in catastrophic failure before the next inspection.

The goal of MVS Technical Challenge is to maintain vehicle safety between these major inspections. The MVS Technical Challenge proposes a three-prong solution to maintain safety between inspections. First, technologies will be developed to enhance existing inspection methods to identify damage in areas that are difficult to access. Second, advanced materials and

coatings, will be developed to prevent damage initiation and growth. Finally, large area inspections, coupled with on-board health monitoring, will identify damage or faults that occurs after an inspection. By providing multiple opportunities to prevent or identify unsafe vehicle health states, current levels of safety can be maintained or exceeded even as air travel demand, vehicle complexity, and the use of new materials increases. The approach is to enable more efficient and effective understanding of the vehicle health by developing health-assurance tools, systems test methodologies, and life indicators targeted for improving the health assessment of a given subsystem, while keeping in mind that a vehicle is an integrated system with notable interplay between subsystems. Further description of the aspects of this approach is given below.



Figure 6.1.—An overview of the Maintaining Vehicle Safety between Inspections IVHAS Approach.

## 6.5    MVS Concept for Integrated Vehicle Health Assurance System

### 6.5.1   Vehicle-Level Concept

To achieve the MVS goal to maintain vehicle safety between these major inspections, the MVS Technical Challenge is decomposed into three elements as shown in Figure 6.2. The Materials and Coatings (MAC) element provides the first line of defense by *preventing* damage initiation and progression to airframe and engine structures through the development of self-healing, self-sensing materials that can prevent or arrest damage progression, and through protective coatings to prevent oxidation and corrosion of advanced engine Ni-base superalloy disks. The Sensors and

Diagnostic Tools (SDT) element provides the second line of defense by *avoiding* and *mitigating* aircraft faults and failures by providing improved inspection methods, coupled with on-board monitoring, to ensure safe vehicle operation between major inspections for the airframe and avionics subsystems. Like SDT, the High Temperature Propulsion Health element avoids and mitigates engine faults and failures, but is unique in that the survivability of the sensors in extreme temperature and vibration environments becomes a significant challenge.
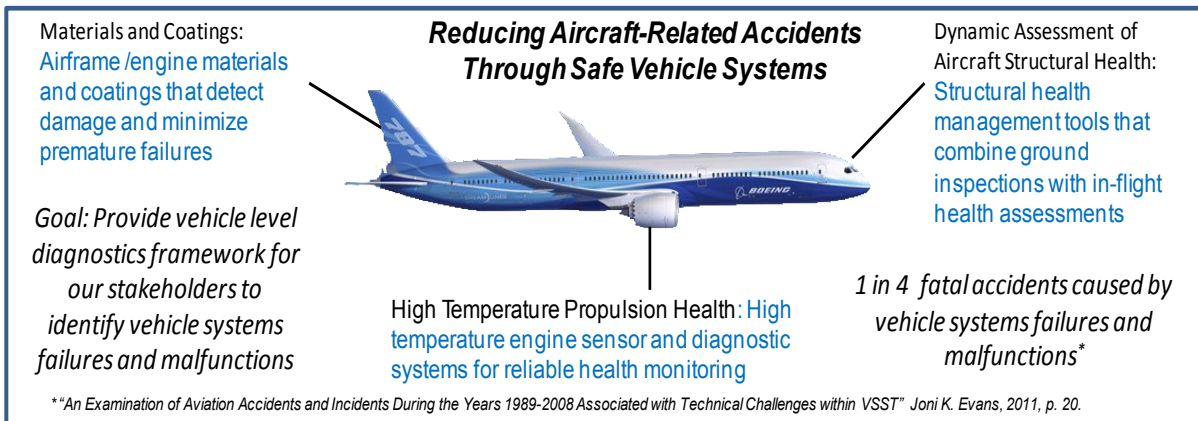


Figure 6.2.—The MVS Development Approach (FY12-FY16).

During FY12 to FY16, MVS tasks and activities will focus on integrated health assurance and failure prevention technologies. Given this scope, the subproject's research products are to develop, evaluate and demonstrate:

- Innovative sensors and diagnostic tools to provide information to anticipate and prevent potential critical failures.

- High temperature engine sensor systems that directly monitor compressors and turbines for reliable engine health monitoring;

- Airframe and engine materials and coatings that detect damage and minimize premature failures from fatigue, fracture, delamination, and corrosion

A fundamental concentration of this MVS project is to take a whole-vehicle approach with emphasis on integrating ground information and history with in-flight detection, diagnosis, and prognosis. The approach is that each vehicle has an individual history ("fingerprint") which spans influences from the basic properties of the materials and components to the vehicle's previous flight history and maintenance records. In order to understand the health state of the vehicle at any given time, it is necessary to take into account not only its present state, but the vehicle's unique fingerprint and history as well. The MVS health state information is fundamental to a whole-vehicle approach that addresses the conditions of a vehicle not only over a single flight, but also realizes that a single flight is a brief snapshot of the vehicle history. This health state information acquired in-flight over multiple flights contributes towards an understanding of the vehicle fingerprint and evolving vehicle state over time thus directly

contributing to the prediction of the remaining useful life of the vehicle. The MVS approach can identify evolving problems in-flight and coupled with ground-based sustainment activities between major inspections, can reduce vehicle maintenance costs and increase availability. (This is in context that any vehicle is part of a fleet of vehicles that also have an individual history; however, fleet wide issues are addressed by SSAT).

The overall MVS framework is shown in Figure 6.3 highlighting the areas of MVS subsystem development over the next five years. The three components of MVS affect the operation of the major subsystems of the vehicle. The Materials and Coatings element affects the airframe and propulsion subsystem with, for example, Integrated Sensing and Healing Systems, Bonded Joints and Repairs, and Engine Emerging Discs and Composite Materials Health. Sensor and Diagnostic Tools affect the airframe, avionics, and propulsion systems with, for example, Digital Assessment of Aircraft Structural Health, Propulsion System Diagnostics, and Wiring Fault diagnostics. High temperature engine sensor systems provide a range of harsh environment sensor and sensor system technologies for improved monitoring of the engine with, for example, High Temperature Smart Sensor systems. Each of the mappings, such as Materials and Coatings to Airframe and Propulsion, is shown in Figure 6.3. The specific technologies chosen for development are chosen based on the safety analysis, the state-of-the-art, NASA capabilities and potential impact, and budget considerations. Further details on the specific research involved are provided elsewhere in Section 6.0.

The results of these technology advancements are intended to provide health state data and allow vehicle level diagnostics. The emphasis of the MVS activities in the next 5 years is on the subsystem level and not on vehicle level diagnostics. However, the MVS development proceeds with the understanding that subsystem technologies will feed into a vehicle level system. This vehicle level system has not been determined, but, without endorsing any particular technology, the basic approach in the NASA sponsored activities described in Figure 5.1 can be considered as a framework. Having such a framework in mind guides the subsystem development in the next 5 years.
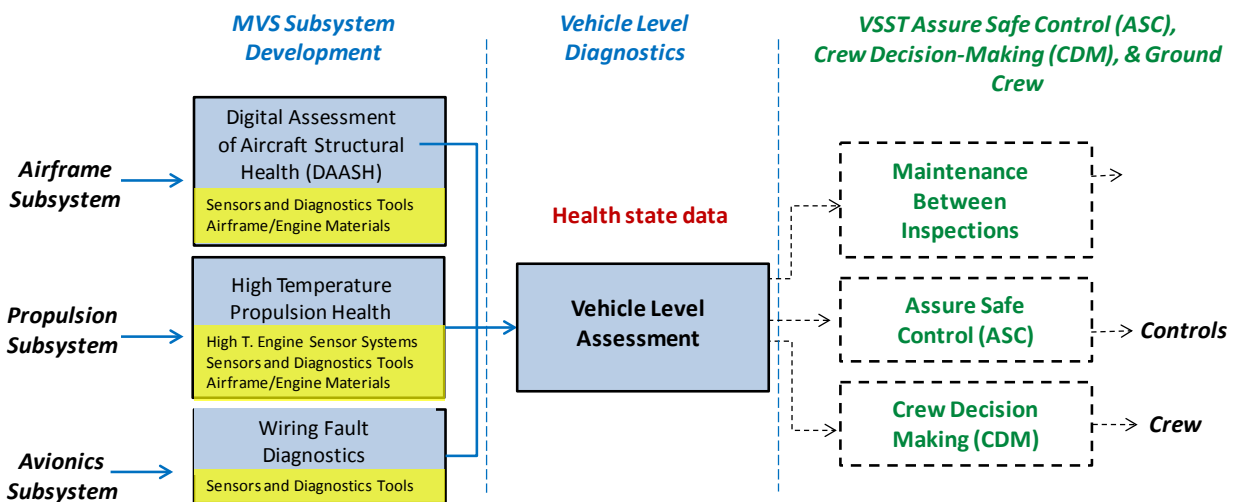


Figure 6.3.—The MVS Integrated Vehicle Health Assurance System framework

The MVS project tools and systems provide information related to the vehicle health state to mitigate and manage the state of degradation of aircraft systems while in-flight and on the ground between major inspections. MVS contributes to an Integrated Vehicle Health Assurance system by providing situational awareness of the vehicle state and condition with combined in-flight and ground information. This allows appropriate mitigation responses to adverse events based on a proper understanding of that particular vehicle system's state in time, rather than attempting to respond to an unknown vehicle condition and perhaps worsen the situation with an inappropriate response. The situational awareness provided by MVS also directly affects response to the ability to enable Crew Decision-Making and Response in Complex Situations (CDM), and Assure Safe and Effective Aircraft Control under Hazardous Conditions (ASC). In other words, in order to make proper decisions in real-time to mitigate a problem, one has to understand the problem; MVS provides information to enable improved decisions.

Further, the effects of MVS are not only for this generation of aircraft systems, but the next generation as well. Next generation vehicle systems will involve new material and technical approaches to enable advanced capabilities. In order for these systems to reach their full potential, the vehicle as a whole needs to include a more intelligent and self-sustaining correcting design concept. Core to an intelligent vehicle is the ability to self-diagnose and self-prognose; the foundation for such capabilities will be developed, matured, and as appropriate, validated as part of the MVS project in specific technology areas.

The MVS Technical Challenge will develop, mature, and validate technologies to detect, diagnose, and prognose the health state of the vehicle while in-flight and on the ground. This is accomplished by sensor systems coupled with algorithms that measure vehicle parameters at the material, component, and subsystem level and analyze those parameters and past history to determine the present health state of the vehicle and predict future conditions. The health-assurance tools developed in this project will target subsystems including airframe, propulsion and avionics, but also other subsystems as appropriate and as resources allow.

The foundation for the overall VSST Health Assurance concept of operations is the combination of an *online* system for storing in-flight sensor readings with processing to identify rapidly failing safety critical systems, and an *offline* historical vehicle database that stores the recorded data regarding a particular aircraft. Added to this is the concept of design enhancements for overall vehicle safety, and that on-board monitoring safety information should be fed to functions such as ASC and CDM, as well as into Inspection Functions and Maintenance Repair and Overhaul Advisories. Fundamentally, this approach addresses the "stove piping" often present in the conventional state-of-the-art (SOA) with a unified strategy combining flight systems, ground maintenance, and design approaches. An overall summary of this approach is shown in Figure 6.4.
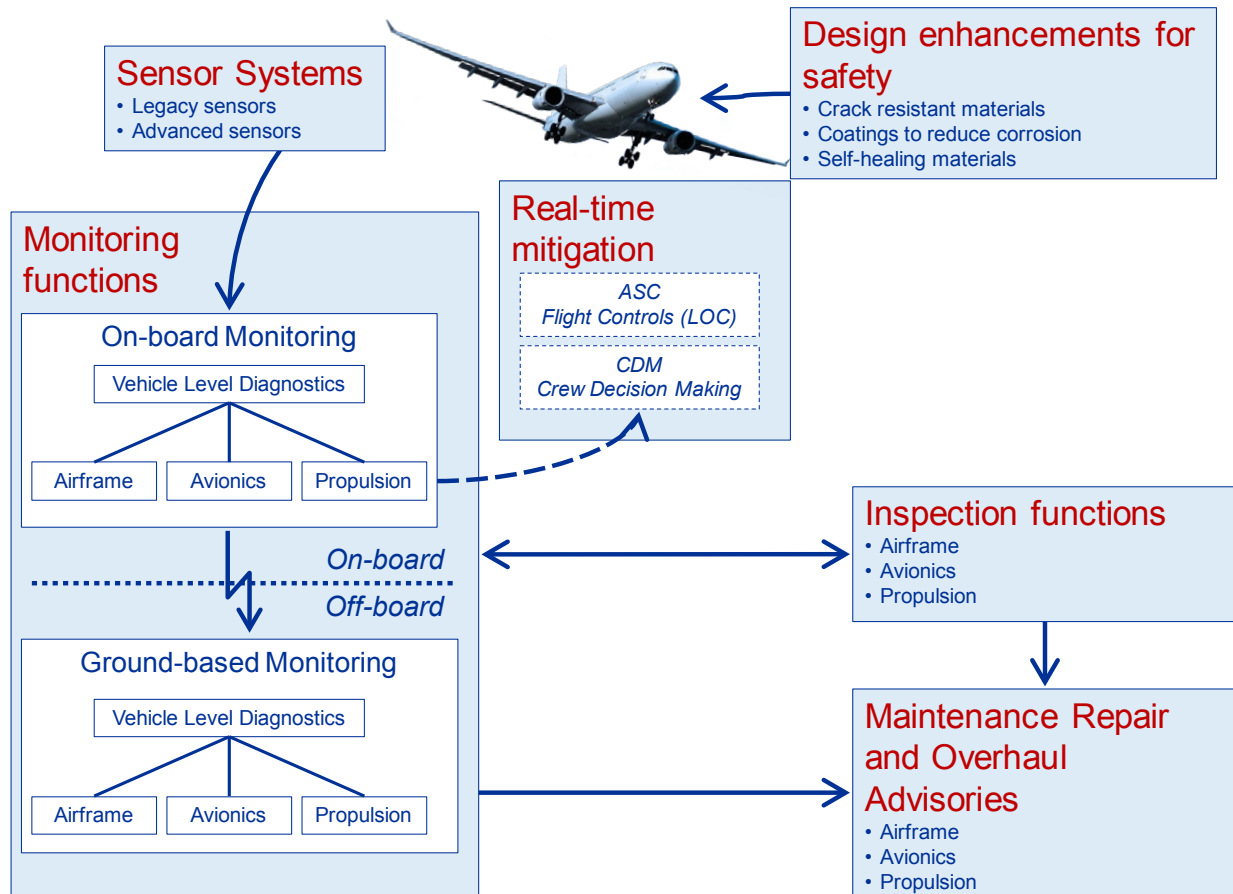
Figure 6.4.—The Concept of MVS Integrated Vehicle Health Assurance, including the integration of design enhancements, improved materials, improved inspection, and onboard monitoring.

The primary purpose of the online system is to collect, locally process, temporarily store, and later transmit flight and environment data to the offline database while at the gate or end of day. A second purpose is to monitor and identify the *rapid* (milliseconds – minutes) degradation and failure of safety critical subsystems that need immediate attention either by the pilot or automation system. The first goal of any vehicle health assurance system is to identify potential failures long before flight safety becomes an immediate concern to the pilot.

The offline historical vehicle database is a fundamental aspect of the overall system. It includes all recorded environmental and flight data (e.g., flight ops/quality assurance data), sensor measurements collected from the aircraft's airframe, propulsion, and avionics subsystems, maintenance records, data sets from ground based inspection, service difficulty reports, and incident and accident reports. Together this set of information forms a digital fingerprint for each aircraft, and enables the identification of custom maintenance actions and/or interventions unique to the history of the individual vehicle.

## User Groups

**Months - Years**
- **Fleet managers** need overall system health information including remaining useful life before major overhaul, and optimal location to schedule repairs.

**Days - Weeks**
- **Maintainers** need state of health information, identification and location of needed repairs, and usage and repair history.

**Minutes - Hours**
- **Pilots** need information and alerting of upcoming safety critical failures and how best to respond.

**Milliseconds - Seconds**
- **Automation Systems** need information for fast engagement to mitigate safety critical failures when the time to failure horizon is so short that human intervention is not possible.

Figure 6.5.—The notional relationship between failure time-scale and the need of various user groups.

The vast collection of data stored in each vehicle database can then be accessed and processed in a great variety of ways, using different applications custom designed to meet the needs of the individual users involved with the day-to-day vehicle operations. There are four major user groups, each with different information requirements: fleet managers, maintenance technicians, pilots, and in-flight automation systems. The health information needs of each group largely depend on the amount of time between the identification of a precursor to failure, and when the actual failure occurs. While in some cases this amount of time can be difficult to accurately predict, what really matters is the time scale. In Figure 6.5, an example of the notional relationship between failure time-scale and the various user groups is illustrated (although the timescales and users may vary given the circumstances).

Finally, the importance of *separating* the storage and processing of the data cannot be overstated. This is because, when feasible, the collected data should be stored to minimize the loss of any information that future improvements to data processing ability may leverage to better assess the

health of the vehicle. Also, errors in processing algorithms can always be corrected without affecting the historical vehicle record.

Relevant health related information for each aircraft can be stored, processed, and managed through a networked database or cloud that users can access from anywhere (e.g., using mobile devices). In particular, sensor data can be wirelessly downloaded when the aircraft lands. This is an important consideration since onboard in-flight computing power is extremely costly to develop, certify, and update. Two brief examples include:

- The flight automation system (through CDM) might interface to the on-board monitoring system and feed information to the flight controls to prevent the aircraft from getting into an upset condition. More specifically, if an impending structural failure is detected the automation system can help the pilot guide the aircraft to the ground while minimizing stress to the weakened components.

- A maintenance application might monitor the recorded electrical power delivered to safety critical avionics systems and generate a specific maintenance action when a significant change to nominal levels occurs. In addition, the long-term historical data can be processed in order to spot trending degradation and the information then provided to a fleet manager.

Data handling will be a major component of any future IVHAS. Maintaining data integrity will be of particular importance. This is followed by the desire to use the data appropriately, including data mining to determine its significance and potentially provide feedback to the system or maintenance actions. Finally, there needs to be an ability to "referee" proper use of the data.

In the hierarchal approach, data processing and analysis will be performed not just in a central location, but at various levels throughout the system. A smart sensor will determine its own health and flag that information as a standard part of the data stream. A local node can take that into account when comparing various sensors in a voting scheme before feeding that information to the subsystem and/or Vehicle Level Reasoner. Finally, local information can be stored and downloaded as needed. The fundamental approach is to move from centralized processing and storage that is overwhelmed with information, to local processing and awareness integrated throughout the system. The three high-level examples below in Section 7.0 go into more detail how various users might interface with the onboard health monitoring system and historical vehicle database.

### 6.5.2 Airframe Subsystem Health Assurance Concept

The cornerstone of the airframe health assurance concept is the Dynamic Assessment of Aircraft Structural Health methodology (DAASH). The long term (10 year+) vision for DAASH is an integrated system that will provide information about actual flight loads and damage not detectable by visual inspection such as multiple damage sites below BVID, or unknown manufacturing defects that might otherwise go undetected and affect the vehicle's structural

integrity. Currently no comprehensive system for structural health monitoring (SHM) of commercial aircraft exists. Most SHM systems in use today focus on areas of known concern, such as monitoring landing gear loads or areas of high stress concentrations. In future aircraft, an onboard SHM system would be capable of real time detection of events that may result in damage and low spatial resolution of the location of damage through changes in the response of the structure. This damage may be due to an impact event, manufacturing or maintenance defects or general degradation of the material system due to aging. During a flight, depending on the level and location of the event detected, the SHM system may initiate maintenance actions after the flight, or in the case of significant damage communicate an estimate of the health state to other onboard systems to limit the operational envelope of the aircraft until it is safely on the ground. Additionally, the SHM indication would trigger the post-flight application of advanced, high-resolution NDE and guide the inspection personnel to the general location of the damage so that a quantitative assessment of the extent and nature of the damage could be performed.

The same SHM system would also provide structural load information to create a record of airframe load history, or as input into control software to prevent excessive operational loads in adverse flight conditions. A record of both vehicle loads and structural health between major inspections would be maintained for the life of the vehicle and could ultimately be used as input to a condition based maintenance program. The onboard monitoring system would remain active during ground operations and provide indications of accidental damage to the vehicle. (For example, a ground vehicle such as a catering truck contacting the aircraft at low speed slowly deforms the aircraft skin over a reasonably large area. The onboard monitoring system would record this event and signal a maintenance inspection before the aircraft would be cleared to fly.) The system would characterize the event and trigger a series of diagnostic and prognostic actions to ensure the vehicle's health, much like the "check engine" light in an automobile triggers additional diagnosis and maintenance to correct the problem. Progressive damage analysis will be used to establish allowable damage limits and critical damage size to define the requirements for the SHM and NDE systems. The coupling of SHM and NDE systems with structural analysis will improve the ability to detect and characterize damage and to assess structural health.

The envisioned comprehensive structural health monitoring system will improve the reliability and safety of future aircraft systems by addressing several limitations in the current approach. An autonomous health assessment system will provide high frequency monitoring and inspection for damage, rather than rely on crew observations or scheduled inspections for damage detection. The system will detect hidden damage from unknown sources and not rely upon visible evidence, which is especially powerful in locations that are difficult to inspect. Integration of SHM, NDE, and residual strength analysis technologies connects execution steps that are now discrete, and thus reduces opportunity for human errors in execution or judgment. Also, an integrated system approach will guide and enable development to achieve system reliability and safety objectives, which is the ultimate goal.

While there are a multitude of threats to aircraft structural integrity, many of these threats will produce obvious indications that immediate action is required (i.e., damage from uncontained engine failure). However, some threats (such as the result of a low speed collision between the

airframe and a service vehicle or a manufacturing defect) do not result in obvious indications of damage, yet may compromise either the structural integrity or the fail-safe capability of the structure. The DAASH element will develop a methodology of assessing the integrity of a composite test article in the event of a single threat that produces no obvious, visual indication of damage. One scenario that is being considered is a partially delaminated stringer. This type of damage could occur as the result of either a manufacturing defect or a large area, blunt body impact.

A demonstration will be used to show how an onboard SHM system, ground based inspection methods of different resolutions (large area rapid low-resolution inspection, localized high-resolution), and progressive damage analysis methodologies can be effectively coupled to characterize the structural integrity of the test article under representative loading conditions. As damage is introduced into the test article, the structural health will be assessed by the integrated system developed. This system could also allow for monitoring of the loads that a panel would experience in order to more accurately characterize the loading conditions. Previous research has focused on independently advancing the SOA in the damage characterization (SHM and NDE) and progressive damage analysis elements, while little work was devoted to integration of these elements into a comprehensive structural health assessment system. Therefore, it is anticipated that although some resources will be applied to advancing the SOA of the individual technologies a majority of the resources will be applied to the integration of these technologies.

The SHM concept is predicated on the detection of damage and quantification of the damage state. To further address the state of the airframe two advanced material concepts are being studied. Self-healing and self-sensing materials are being developed to prevent damage from initiating or propagating and to improve damage detection by developing materials that facilitate damage detection using existing sensor technology. The self-healing material concepts that are being addressed specifically mitigate damage from propagating in polymer matrix composites after impact and fatigue crack growth in metallic materials, which are two of the most likely damage scenarios for airframe materials. The detection of damage in structural materials is inherently difficult as the critical size of damage can be quite small and present within very complex geometries. Consequently, it is desirable to design materials that augment the capabilities of existing sensors. Materials that emit an audible signal when damaged, which can be monitored by passive on-board sensors, are being developed. Additionally, these materials have demonstrated improved signal detection of damage when using ground-based inspection techniques. These self-sensing materials are being studied to augment the SHM concepts being developed within the DASSH portion of the project.

As indicated in the above description, the proposed methodology for assessing aircraft structural health uses a layered approach for damage detection. In addition to an on-board system for course indications and localization of damage, the DAASH element includes demonstration of rapid large-area ground inspection technology. The ground-based system would provide more detailed assessment of airframe health in response to a reported ground or in-flight event prior to the next flight, or provide a supplemental capability to an on board SHM system to daily 'scan' the structure for the development of damage from any unknown cause (i.e., inappropriate

maintenance action or repair, manufacturing defect, or high stress location). The current health assessment would then guide contingency actions in flight or further diagnostic or repair actions if needed. A notional block diagram of one embodiment of this response is shown in Figure 6.6.



Figure 6.6.—Notional block diagram showing one way the Dynamic Assessment of Aircraft Structural Health (DAASH) technologies might integrate into an overall vehicle health system.

As indicated in the above description, the proposed methodology for assessing aircraft structural health uses a layered approach for damage detection. In addition to an on-board system for course indications and localization of damage, the DAASH element includes demonstration of rapid large-area ground inspection technology. The ground-based system would provide more detailed assessment of airframe health in response to a reported ground or in-flight event prior to the next flight, or provide a supplemental capability to an on board SHM system to daily 'scan' the structure for the development of damage from any unknown cause (i.e., inappropriate maintenance action or repair, manufacturing defect, or high stress location). The current health assessment would then guide contingency actions in flight or further diagnostic or repair actions if needed. A notional block diagram of one embodiment of this response is shown in Figure 6.6.

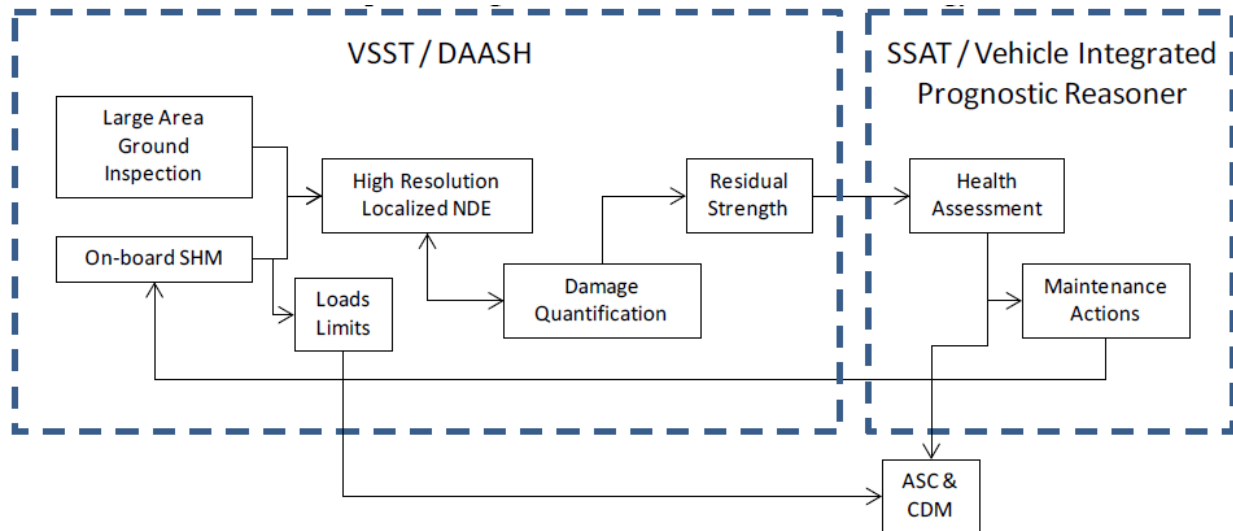The individual components in Figure 6.6 represent technologies and methodologies that will be integrated as part of the Airframe Health Assurance element and will be integrated together in the final technology demonstration on a laboratory-scale test article.

Impacts of the Airframe Health Assurance Approach include:

- On-board SHM—Demonstration of how SHM can be used for impact detection, load monitoring, or damage localization.

- Large Area Ground Inspection—Demonstration of how rapid, large area ground-based NDE inspection could be used to enhance safety between inspections with little or no downtime to the aircraft unless damage is found. This could be used in place of an SHM system in legacy aircraft, or to complement the SHM system.

- High Resolution Localized NDE—Demonstration of how high-resolution NDE can provide detailed, quantitative information regarding physical characteristics of the damage.

- Damage Quantification—Demonstration of how model driven, combined NDE, SHM data and/or inverse FEM methods can be used to quantify damage size, type, and location.

- Residual Strength—Demonstration of the prediction of damage progression, residual strength and critical damage size.

- Load Limits—Demonstration of how load information could be provided as input to determine if updated load limits are required based on reduction in residual strength and/or an accumulation of damage for continued operation of aircraft until it is safely returned to the ground.

- Durable Materials—Demonstration of self-healing materials capable of mitigating representative damage for replacement on existing aircraft structure or for integration in the manufacture of new vehicles.

### 6.5.3 Avionics Subsystem Health Assurance Concept

Any overall avionics health assurance concept of operations must be general enough to incorporate information from a diverse array of electronic sources, and the historical vehicle health database provides the backbone for this functionality. This is because each individual subsystem can store its own electronically measured health information offline, without necessarily needing to interact with any other subsystem. Applications can then process the data for either the individual system, or across multiple subsystems, to provide diagnostics and prognostics capability. The only data processing required on-board would be to detect rapid damage progression leading to an imminent failure that demands the immediate attention of the pilot or automation system.

### 6.5.3.1    Electrical Wiring and Interconnect System Health Assurance System Concept

From a bird's eye view, the *hardware* technology required to setup health management for the wiring and interconnect system is available now. It is the same technology summarized in Section 5.3. However, new or modified design concepts are required to unify these technologies from the ground up, especially for systems to benefit from chafing fault detection.

An initial concept only requires the integration of sensors to measure and store signal integrity and power consumption information both during flight, and while the aircraft is on the ground. These sensors would need to be incorporated into the power distribution and interconnection of critical avionics systems. The information collected by the sensors could then be transmitted to the vehicle historical database in between flights for on-the-ground processing and analysis to determine if maintenance actions are required. This approach minimizes the need for additional in-flight computing power, and should be completely separate from the hardware and software required during flight. In other words, during flight the EWIS health management system need only passively record data. Furthermore, the electrical system can be electronically inspected for chafing through the use of a built in system that functions while the aircraft is in a quiescent state on the ground. While this on-board system would enable a fast inspection of the typically inaccessible wiring, it would not be considered an in-flight system.

To a certain extent, industry already appears to be moving in this direction. For example, Gulfstream and Boeing are already reporting the use of solid-state power distribution systems capable of load monitoring for health management [61, 62]. From a hardware standpoint it seems a relatively straightforward process to integrate the additional sensing electronics required for intermittent connection detection, (which requires monitoring in a vibrating operational environment), and chafing fault detection (which is probably best performed while the aircraft is in a quiescent state). What's needed is the integrated system for collecting the data, along with health management modeling and diagnostics/prognostics algorithms. To a large extent, the tight coupling between data collection and software processing is a major bottleneck to the advancement of integrated health management. This is because the health management models and algorithms driving the data collection requirements are still under investigation within the research community.

### 6.5.3.2    Other Avionics Health Assurance Systems Concepts

Health assurance for safety critical avionics boxes, electromechanical actuators, and batteries has the potential to span the timescales of all user groups presented in Figure 6.5. Health management algorithms with prognostic horizons longer than a few flights can be used by maintainers to perform condition-based maintenance and by fleet managers to position assets more effectively, taking into account that some assets will be unavailable because of upcoming maintenance. At the other end of the timescale, diagnostic algorithms or prognostic algorithms with short horizons can inform pilots and automation systems. For example, if an actuator jam is detected, a low-level automated control reallocation may be required to maintain aircraft stability.

Research in health assurance for actuators, batteries, and avionics boxes is still establishing the types of sensors and processing requirements needed to perform robust health management. In some cases, accurate, high-confidence diagnostics and prognostics may require additional instrumentation that is not typically found in fielded systems. For example, installing accelerometers on electromechanical actuators can lead to more accurate fault diagnosis and prediction of remaining useful life. However, installation of sensors that are not required for subsystem control is undesirable from an aircraft integrator perspective because sensors require power, calibration, interpretation, servicing computer memory and processing time, wiring, weight, and volume [192]. Similarly, high data sample rates and intensive processing power required by some algorithms pose challenges to on-board implementation.

An initial concept for health management of these avionics system involves three aspects. First, additional instrumentation and data storage capabilities should be deployed in a research context to establish the signatures of faults and precursors of failures. Such data would be downloaded and analyzed off-line to evaluate the potential of various feature extraction approaches and health management algorithms. Second, correlations between research instrumentation and typical fielded instrumentation in regards to health management capability should be assessed. The ultimate goal is to find sensing and analysis approaches that use available instrumentation and processing to the extent possible while still providing sufficient health management capabilities. Improvements in sensing and processing capabilities will continue to expand the possibilities in this regard. Third, an approach to store short bursts of higher rate data on-board for off-board processing would address the difficult problem of no-fault found, where on-board summary fault indications cannot be replicated in a quiescent test environment. In this scenario, a circular buffer of high rate data that is normally overwritten would be preserved when a trigger condition is met. It is important to record environmental parameters to understand the conditions under which the equipment was operating when the fault occurred. This approach is already being pursued by General Electric [193]. As noted in the previous section, arriving at the proper sensing, data collection and software processing requirements is necessary to advance integrated health management. The concepts outlined above should help to address this need.

Impacts of EWIS Health Assurance Approach include:

- Industry could focus on in-flight sensing and data collection, transmitted for database storage and processing on the ground. Geared towards detecting intermittent connection problems that require measurements in an operational vibrating environment.

  o In particular, new avionics boxes should actively communicate connection status to power distribution centers in-flight. This approach might work well with the solid-state power distribution methods currently going into practice.

- Chafing fault detection on critical signal and power wires only, can be used to electronically ensure cable integrity and prevent incipient problems.

  o Implementing this step may require additional wiring requirements (shielded, impedance controlled, etc.) for the target critical systems, but would also help ensure safety and enable faster, more targeted condition based wiring maintenance. It would enable one to verify before each flight that the most critical wires on the aircraft are intact and ready.

  o Watch points can be established and monitored for increasing likelihood of a small chafe, and later growing size of the chafe. Fleet managers may be able to determine when to make bulk repairs.

### 6.5.4 Propulsion Subsystem Health Assurance Concept

The harsh environment conditions within an engine often present significant challenges for the integration and application of health management systems. In parallel, diagnostic systems often have to perform evaluations with limited sensor information, while evaluating a complex system whose components include gas path, turbomachinery, hydraulics, and other components. The approach to Propulsion Health Assurance consists of a combination of activities in Engine Emerging Discs and Composite Materials Health, Propulsion Systems Diagnostics, and Smart High Temperature Sensor Systems to be described below. Propulsion Systems Diagnostics provides methods for the real-time assessment of the overall health of the engine. This includes assessing engine aero-thermodynamic performance, and the health of turbomachinery blades and vanes, control sensors, and control actuators. Smart High Temperature Sensor Systems include sensors and sensor systems, which allow the measurement of engine parameters in harsh conditions allowing for improved understanding of the engine state. Both tasks feed into continued Vehicle Integrate Propulsion Research (VIPR) testing. These activities provide information related to gas path and rotordynamic areas identified as associated with safety risks: engine compressors, turbines, gas path, bearing/seals, and overall engine health. These are intended to diagnose and monitor engine systems and mitigate potential issues through existing and new easily integrated, small, low weight sensors avoiding costly retrofits while maintaining

safety. This basic approach is shown in Figure 6.7, which illustrates the combination of increased sensor coverage and improved sensor diagnostics to improve understanding of the engine health state.
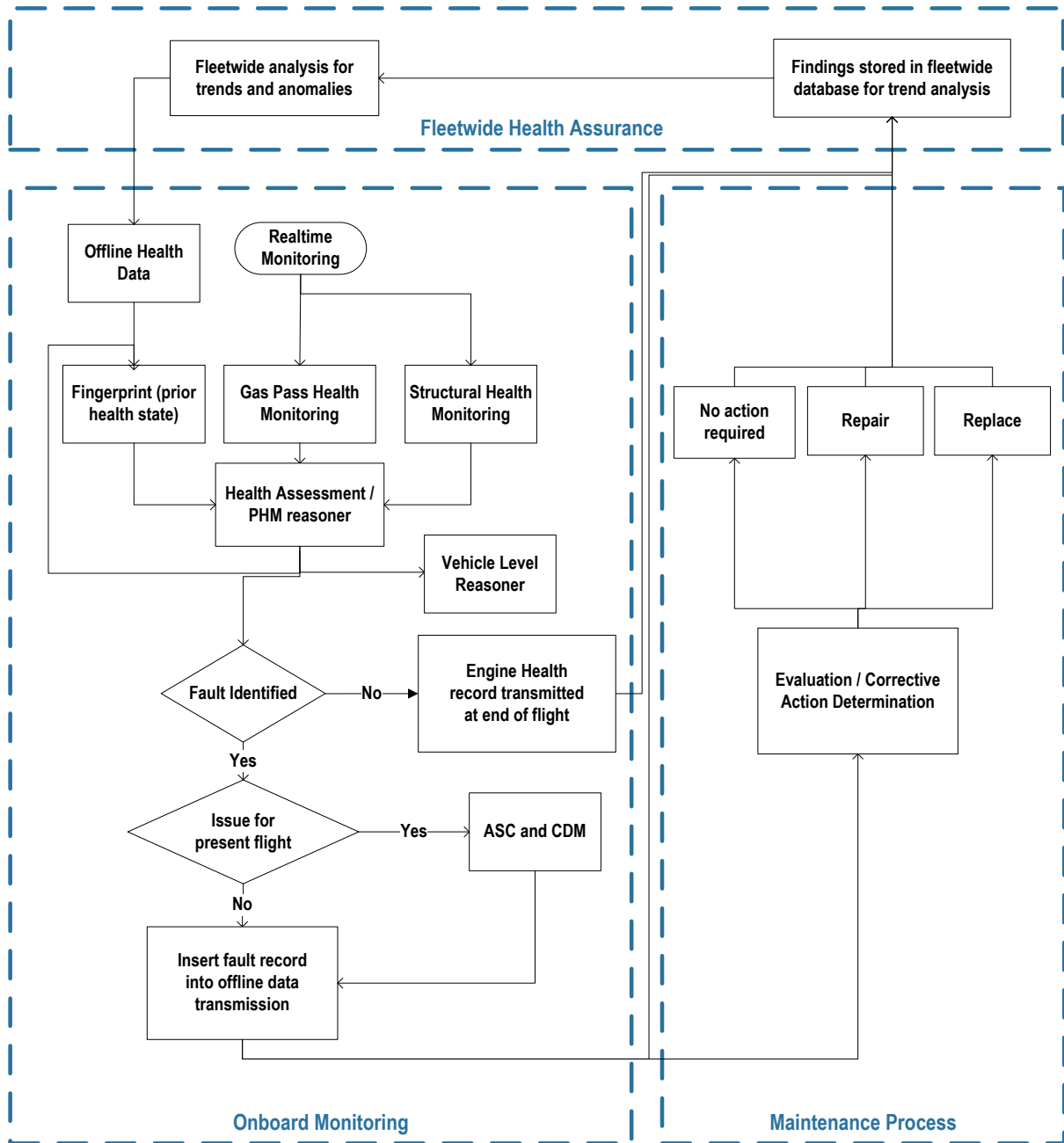


Figure 6.7.—Notional block diagram of Propulsion Health Monitoring Assurance Concept.

### 6.5.4.1 Engine Emerging Discs and Composite Materials Health

Current and emerging commercial aircraft are utilizing advanced materials in propulsion components including advanced Ni-base superalloys for turbine disks and polymer matrix composites for engine structures. This Task addresses potential safety issues for recently implemented technologies as well as robust design for future emerging technologies. Accurate life prediction, taking into account materials, component design, manufacture, flaw detection, and service conditions, is a goal. A turbine disk failure usually results in a loss of engine, considerable airframe damage, and the possibility of loss of the aircraft. A detailed characterization and modeling of the near surface layer after current and advanced surface processing, including application of coatings, is needed for more accurate life prediction. Linkage of life prediction and microstructure prediction models will be performed to discern what features in the microstructure and surface conditions govern and limit fatigue life for the relevant service conditions. Composite materials are beginning to be used for fan cases and other engine primary structure. There is little service experience with composite components, and failure mechanisms are not well understood. Technologies will be developed to provide a more robust assessment of safety for these composite engine structures, for both current and future applications. Potential effects of material aging in simulated engine environments and impact damage from various sources (bird strike, hail, FOD) in order to assess safety over the full life cycle of an engine will be investigated.

### 6.5.4.2 Propulsion System Diagnostics

Propulsion Systems Diagnostics are provided for the assessment of overall engine health. This includes enhanced gas path and rotating structural health diagnostic capabilities. Propulsion Gas Path Diagnostics is performed by relating observed changes in sensed engine parameters to internal performance-related changes within the gas turbine engine cycle. Monitoring and processing engine sensed measurements enables the detection and isolation of problems, ultimately enabling corrective action to be taken. Rotating structural health diagnostics is performed by applying and analyzing the measurements collected from advanced sensors installed for monitoring the dynamic response of the engine structure. This includes blade tip clearance, tip timing and tip clearance measurements as well as advanced accelerometer measurements.

This work directly addresses limitations in propulsion diagnostics capabilities. Today, propulsion gas path health management (GPHM) functionality resides both onboard and off-board the aircraft and is primarily conducted relying on the sensors installed for engine control purposes. Onboard GPHM functionality applies relatively simple range and rate-of-change checks to diagnose engine fault conditions. Off-board, or ground-based, GPHM processes a limited number of "snap-shot" measurements collected at fixed operating points from each engine each flight to trend engine performance deterioration and to diagnose gas path system faults. However, this off-board processing often does not happen until several days after the flight has occurred causing significant diagnostic latency. Additionally, any resulting engine performance deterioration estimates are only available off-board. They are not available for on-board controls and health management applications, and thus are not utilized to their full potential. In addition,

very little instrumentation exists for the in-situ structural health monitoring of engine components. Most of the structural monitoring is done by secondary instrumentation such as low frequency accelerometers to monitor vibrations and other sensors that are used by the control system. Actual, detailed, structural health monitoring is done offline by physical inspections of the engine components on a periodic basis defined by a maintenance schedule. Correspondingly, there are a range of in-flight engine propulsion system malfunctions that can occur. Examples include turbomachinery damage, control sensor and actuator faults, and turbomachinery deterioration induced by environmental effects such as volcanic ash and ice ingestion.

The approach in propulsion diagnostics is to address the imperative need for aircraft operators and maintenance personnel to have accurate information regarding the health state of the engine gas path system in order to make appropriate maintenance and inspection decisions. Additionally, propulsion health state awareness can assist the flight crew in recognizing and responding to engine malfunctions. In the past, propulsion system malfunctions combined with inappropriate crew responses has contributed to a number of Loss of Control (LOC) accidents, rejected takeoffs, and crew errors such as shutting down the wrong engine. Engine gas path diagnostic strategies are needed that can enable continuous real-time monitoring of engine health; estimation of unmeasured engine performance parameters for diagnostics, prognostics, and controls applications; and overall improved propulsion health state awareness to support crew system decisions and LOC prevention/mitigation strategies. This work will develop and mature on-board model-based aircraft engine estimation and diagnostic technology.

### 6.5.4.3    Smart High Temperature Sensor Systems

A critical first step in any health management process is the acquisition of physical system measurements via sensors. State-awareness is the foundation of diagnostics and decision-making, and present aircraft propulsion systems have limited self-awareness due to the harsh environment operational condition. Given the range of relevant engine component parts whose failure can have a notable impact, there are a range of parameters that are of interest to measure in an operating engine. Presently very few of these parameters are measured and often with systems whose implementation is restricted by the harsh environment conditions, implementation on rotating components, or both. Sensor reliability is a significant issue with wiring being a dominant cause of sensor failure, leading to limitations in the implementation of sensor technology.

The development of Smart High Temperature Sensor Systems focuses on the design and fabrication of sensors that can withstand the extreme temperature environment of engine gas path and rotordynamic components including compressors and turbines. The engine is a complex system with a range of operating components whose failure can affect passenger safety. This work will produce a multiparameter array of harsh environment compatible sensors able to monitor a targeted range of relevant static and rotating components that presently are not reliably monitored or cannot be monitored during flight. The approach is to integrate these sensors and sensor systems into a multiparameter detection suite whose combined information provides engine characterization significantly enhanced compared to that provide by a single, or single

type of, engine sensor. Included is development of high temperature electronics, communication, and power to enable a smart sensor system moving toward the "Lick and Stick" concept described in Section 5.4.2.3.6. This work concentrates on the development of sensor technology to enable their maturity as engine diagnostic tools as well as improved sensor reliability and capability for viable engine implementation. This work will focus sensor development on different aspects of engine operation. It is not possible within this task to provide technology to characterize the entire engine; rather as described in Section 6.6.4.2 specific engine properties are targeted with relevance to safety issues, applicability to engine diagnostics, lack of existing flight measurement capability, and potential for vehicle integration.

### 6.5.4.4    Information Fusion for Propulsion Health Management Systems

Current aircraft gas turbine engine health management systems are comprised of a diverse assortment of diagnostic modules designed to assess the health of individual engine subsystems such as gas path system performance, structural health, and lubrication system health. Continuing advancements, as previously described, in sensing technology are providing the potential for additional engine health state information such as turbomachinery clearances, combustion chemical emission content, high frequency vibration measurements, and gas path debris indications. Currently, there is no well-established means for combining this information to produce an overall system-level assessment of an engine's health.

An information fusion capability as a means for combining health information from multiple engine subsystems, available in different formats, and updated at different frequencies will be developed. The information fusion architecture will be modular in design, permitting additional diagnostic subsystems to be added as they become available. In particular, approaches for combining gas path performance, turbomachinery clearance, and chemical emission information will be studied in the near term. This will provide a baseline tool to allow integration of information on the propulsion subsystem that will then feed towards a larger vehicle health management system providing in-flight information on vehicle health in an easy-to-use format. The approach is to provide information fusion of the wide range of input parameters specific to propulsion systems.

Impacts of the Propulsion Health Assurance Approach include:

- Advanced powder metallurgy (PM) disk life prediction algorithm taking into account effects of production and service conditions.

- Environmental protective coating for advanced PM superalloy disks providing new capabilities to minimize premature fatigue failures from corrosion and oxidation

- New inspection methods, standardized analysis methods, and identification of potential composite material /structure failure modes in service providing the tools needed for airworthiness assessment and failure mitigation

- Focus on technologies for the reduction of safety-significant propulsion malfunctions that have contributed to past propulsion system malfunction plus inappropriate crew response accidents, such as asymmetric thrust, rejected takeoffs, and in-flight engine shutdowns.

- On-board model-based gas path diagnostic architecture combined with an adaptive self tuning engine model providing in-flight capabilities to diagnose engine health state and prevent in-flight propulsion malfunctions.

- Provide diagnostic benchmarking problems and metrics leading the engine community in standard approaches and practices.

- Multiparameter harsh environment engine sensor suite for comprehensive detection of compressor, turbine, and rotor failure precursors.

- High temperature Smart Sensor Systems with in-situ processing and communication capabilities leading to new measurements and more reliable sensor data.

- Evaluation of data from multiparameter engine sensor systems in both simulated and real fault conditions.

- Information fusion approaches to combine a range of propulsion system information.

## 6.6 MVS Concept Development and Implementation Plan

The MVS Technical Challenge has several major milestones representing progress toward achieving the goals identified above. The overall approach will be developed in FY12, with this Concept of Operations document outlining a detailed plan for developing an integrated vehicle health approach and demonstrating the survivability of engine sensors in extreme environments. In FY13, the focus is on diagnostic methods for identification of both airframe damage and off-nominal engine operation. FY14 further advances the SOA by predicting damage progression and improved methods for repairs to prevent damage progression. The effectiveness of these

methods will be integrated, demonstrated, and evaluated at the subsystem level in FY14, culminating in integrated demonstrations in FY15. These milestones address the major vehicle-related factors that directly or indirectly cause fatal accidents and provide multiple layers of safety, from prevention through mitigation. Collectively, this will result in an effective approach for maintaining or improving vehicle safety between major inspections.

### 6.6.1 Vehicle System Development and Implementation

### 6.6.1.1 Vehicle System Approach

The implementation of the IVHAS across the vehicle is a long-term activity that first concentrates on subsystem development and then expands to increasingly complex vehicle level systems with continual feedback between design and maintenance activities. Research deliverables associated with these products include prototype sensors with associated failure prediction algorithms, prototype materials and coating subsystems, peer-reviewed publications of interim research results, guidelines and recommendations, and performance metrics. An overview of a timeline related to this MVS IVHAS development is shown in Figure 6.8.
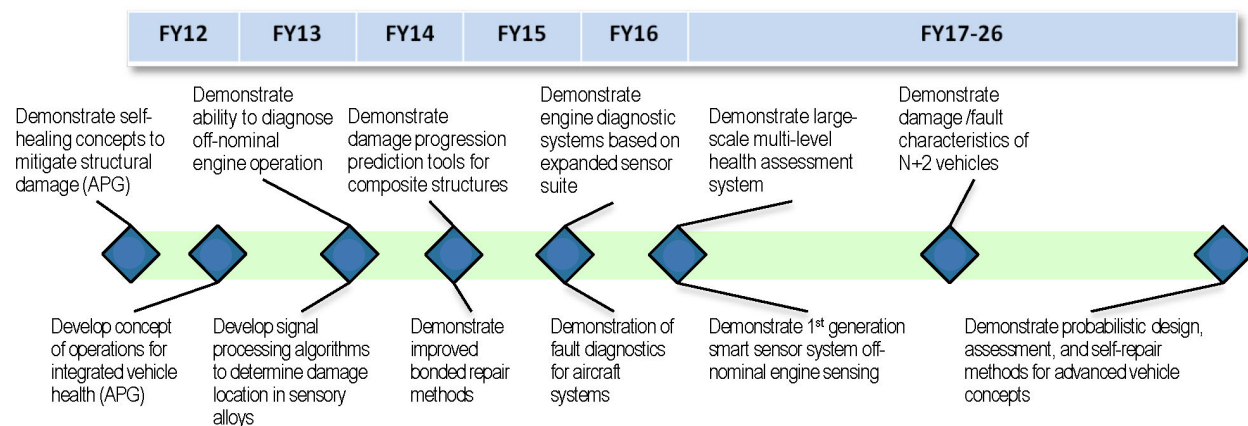


Figure 6.8.—Development of IVHAS over the next 15 years.

The milestones map advances the development of technologies that enable safe aircraft operations between inspections over the 15 year time span. Specific benefits include: (1) Reduced in-flight safety risks due to engine, airframe, and avionics related faults and failures; (2) Individual vehicle health-state awareness supports better in-flight decisions and targeted ground based maintenance. The milestones delineate progress in the areas of new materials and coatings for assuring structural integrity for safe operations; methods for early detection of vehicle hazards through increased monitoring capabilities using sensors designed for extreme environments and increased sensor density; and integration of ground-based inspections with real-time in-flight health monitoring of aircraft systems.

The MVS Technology Challenge has a pipeline approach of technology development and maturation. Within a given technical area, there is a mixture of both more mature and less mature technologies. The more mature technologies can be brought to the demonstration stage, e.g., an on-wing or flight demonstration, during the course of the program, perhaps early on. Other

technologies are less mature at the beginning of the program, but are planned to be advanced for demonstration at the end of the program. Finally, a smaller portion of the technology is meant as a foundation for the next phase of the Aviation Safety program to begin to have impact early in its implementation.

The demonstration activities are meant to both advance the maturity of the technology, but also provide a method to begin the process of hand-off to potentially interested industry sources. In order to collaborate and advance technology, NASA continuously maintains and establishes new external partners through Space Act Agreements (SAA), NASA Research Announcements (NRAs), and Small Business Initiative Research (SBIR).

Currently the Aviation Safety Program's System-wide Safety Assurance Technologies Project is developing a Vehicle Integrated Prognostic Reasoner that is aimed at providing knowledge, concepts, and methods to proactively manage increasing complexity in the design and operation of vehicles and air transportation systems, including advanced approaches to enable improved and cost-effective verification and validation of flight-critical systems. It is also anticipated that MVS will leverage this development activity through collaboration with the SSAT Project.

The work under the MVS Technical Challenge supports the research ongoing under the broader VSST Project. The other two VSST Technical Challenges, CDM and ASC, are focused on reducing human factor and loss of control related accidents, respectively. System and component failures are often a contributing causal factor in these types of accidents. The first line of defense provided by MVS is the early incipient diagnosis of impending faults, enabling corrective maintenance to be performed prior to the event escalating into an in-flight malfunction. Additionally, MVS can supply real-time on-board vehicle malfunction and health state information. Such information can aid in crew decision-making, and can also help to avoid or recover from loss of control scenarios. An example of how the MVS work relates to the research ongoing under the CDM and ASC Technical Challenges is given below, and is also discussed elsewhere in Section 6.0, and in the scenarios in Section 7.0.

A propulsion accident category related to the CDM Technical Challenge is Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR)—an event where the pilot(s) does not appropriately handle a single benign engine system malfunction [194]. Example PSM+ICR events include shutting down the wrong engine, rejected takeoff, and loss of control where a PSM is a contributing factor. In the event that an in-flight PSM does occur, engine health management technology can aid in pilot decision-making by detecting and, when appropriate, providing an indication of the malfunction. Recently, an FAA contracted effort with Boeing was performed to assess the concepts, risks, issues, technical feasibility and operational appropriateness of providing indications of propulsion system malfunctions to the flight crew [24]. This study specifically considered the detection and annunciation of engine powerloss, surge, failed-fixed thrust, high vibration, and thrust asymmetry. NASA is developing and evaluating diagnostic techniques related to several of the PSM indications considered in the FAA-Boeing study. This includes vibration diagnostics (high vibration), detection techniques for identifying a mismatch between commanded and delivered engine thrust (powerloss and failed-

fixed thrust), and detection techniques to identify the occurrence of asymmetric thrust when auto-throttles are engaged (thrust asymmetry). Reliable detection while avoiding undue complexity will be points of emphasis in this work. Additionally, MVS will coordinate with CDM to assess human factor issues and operational risks associated with PSM indications.

Under the ASC Technical Challenge, NASA is investigating integrated flight and propulsion control concepts to help avoid and mitigate LOC scenarios. This includes enhanced engine control modes such as engine overthrust and faster engine response to enable "propulsion assisted" flight control [195-197]. In order to extend engine operation without incurring unacceptable risk, the current health state of the engine must be known. This health information can be provided through ongoing work within the MVS High Temperature Propulsion Health Management element. Specifically, the self-tuning on-board engine model technology provides an estimate of the level of performance deterioration within each individual engine. This information can in turn be used to estimate available engine thrust and operability margins for use by the control system. MVS is coordinating with ASC to supply the propulsion health state information that is necessary to enable enhanced engine control modes in support of integrated flight and propulsion control research.

## 6.6.2   Airframe Development and Implementation

In order to move toward the long-term vision, the proposed 5 year DAASH task for VSST will focus on the development and integration of SHM, NDE and structural residual strength analysis technologies to enable a quantitative assessment of airframe structural integrity between major inspections. At the end of the 5 year period, this element will culminate with the coordinated demonstration of these technologies on a test article, showing how an integrated assessment of structural health could be accomplished. It is anticipated that the test article will be obtained through a partnership arrangement thus allowing us to leverage engineering and design of the test article. Potential partners include Boeing, USAF, FAA and other NASA Aeronautics programs.

The goal of the DAASH task is to demonstrate technologies and integrated systems that can reduce risks in future aircraft. The emphasis will include threats to the operation of aircrafts composed of composite materials. Based on perceived safety threats, the highest risk threats to composite airframe structural integrity are:

- Discrete source damage from ground vehicle impact, bird strikes, hail, runway debris and uncontained engine failure.

  - Large scale damage posing immediate threat

  - Small-scale damage that may be undetected and accumulate or grow over time/cycles

- Other sources of small-scale damage that may grow undetected: manufacturing defects, local high stresses, tool drops, and inappropriate maintenance

It is anticipated that the DAASH element will focus on panel structural health or capability, while the SSAT reasoner or its equivalent will manage structural subcomponent health as one of

many subsystems, and will assess vehicle health based upon subsystem health and interactions of the subsystems. This collaboration will lead to an integrated methodology for maintaining aircraft structural safety between major inspections.

- Health Assessment—Assess overall health and determine if any in-flight actions need to be taken or provide guidance for maintenance items (includes development of a safety metric for qualitative contingency management)

- Maintenance Actions—Provide additional health history data to maintenance depot

- ASC and CDM—Health state awareness for Assure Safe Control (ASC) and Crew Decision-Making (CDM) Technology Challenges.

Additional partners must be identified and secured early in the project cycle to either leverage other structural test programs or partner with external organizations for access to structural test specimens or systems engineering support for test article development and the integrated demonstration. Activities that will build up to the final demonstration will also require the fabrication of task specific composite structures, SHM and NDE components. This may require significant collaboration and partnership from close industry sources. During the initial year of execution, activities will be initiated to identify and begin procurement of the appropriate test article and subcomponents necessary for the technology demonstration. The demonstration will showcase the integrated operation of multiple activities in the program, and seeks to simulate how these technologies might be applied in a real aircraft experiencing a series of operational conditions. It is anticipated that this demonstration may take place over a period of days or even weeks.

High-level task milestones as well as some notable lower-level activities are shown below. Additional sub-team or branch level milestones, approximately one per year per sub-team or branch, are being developed that will support the task level milestones. These milestones are described below and shown in Figure 6.9.
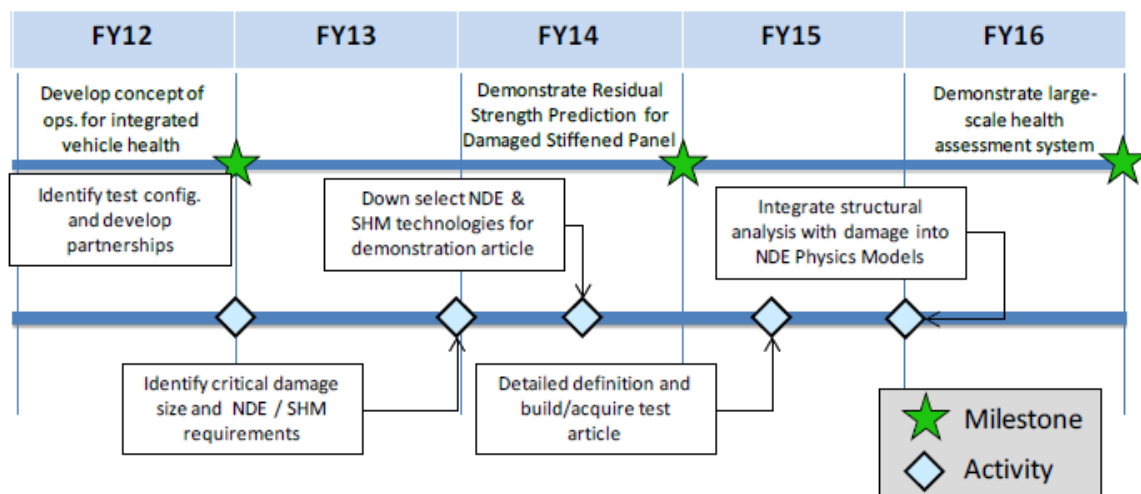


Figure 6.9.—Air Frame Health Assurance Milestones.

**FY12:**

- Develop concept of operations for integrated airframe vehicle health management—A document describing the overall approach to the MVS Technical Challenge and how the DAASH concept could be integrated with other subproject elements and tasks.

- Identify test configuration and develop partnerships—In order to maximize the use of available resources, it is anticipated that the test article will be obtained through a partnership arrangement thus allowing us to leverage engineering and design of the test article and any associated hardware.

**FY13:**

- Identify critical damage size and NDE/SHM requirements—Conduct progressive damage/residual strength analysis to determine critical damage sizes for selected region(s) of aircraft structure and loading condition(s). Critical damage sizes determined will derive NDE/SHM detection requirements. Additionally, resources permitting, assess fidelity of analysis predictions using damage characterization from variable fidelity NDE methods as input.

**FY 14:**

- Down-select NDE and SHM technologies for demonstration article—Based on the requirements for critical damage size, a suite of NDE and SHM technologies will be selected that will be integrated into the final demonstration test article.

- Demonstrate residual strength predication for damaged stiffened panel—Develop and demonstrate progressive damage analysis capability for predicting the residual strength of a damaged multi-bay stiffened bay panel subjected to compression loading. Activity will include pathfinder experimental investigations at the coupon and element level to identify fundamental damage mechanisms and their interactions for compression loading. Building-block test matrix will be developed for characterization of input required for damage models and for validation of analysis model developments.

**FY15:**

- Detailed definition and build/acquire test article—This activity will finalize the definition of the test article and any associated hardware necessary for the final demonstration.

- Integrate structural analysis with damage into NDE physics models—this activity will facilitate a closer integration of the structural analysis with the NDE, where the results of damage progression models are used by NDE researchers to determine both the fidelity requirements for an inspection technique and the actual technique and data analysis methodology used.

**FY 16:**

- Demonstrate large-scale health assessment system—This final activity of the task will be a demonstration of how integrated assessment of structural health could be accomplished. This test article will validate not only the individual technologies (such as on-board

SHM, large area NDE and progressive damage analysis) but will demonstrate how an integration of these technologies will provide overall assessment of the health and strength of the panel.

### 6.6.3 Avionics Development and Implementation

The field of aviation electrical systems is incredibly broad, and no one resource limited project could adequately address the diverse set of health management issues encompassed within it. However, the above discussion should have made clear that most of the important issues are being addressed by a diverse collection of government and industry partners working together through a variety of funding sources. In the next section, we provide a detailed discussion of the novel approach and its planned implementation for the wire chafe detection work currently funded through the Vehicle Systems Safety Technologies project. This is however just one small piece of the overall picture. The Aviation Safety Program's System-wide Safety Assurance Technologies project currently funds much of the research and development of applied algorithms for batteries, electronic components, and electromechanical actuators discussed above.

In the Safety Factors section, the Electrical Wiring and Interconnect System (EWIS) was shown to be a historically notorious common point of failure that affects nearly all types of avionics equipment. Furthermore, with modern jet aircraft containing 100 to 200 miles of wire [198] the EWIS is a large system in great need of automated health assessment technology. The current SOA is limited to the detection of hard faults (i.e., opens, shorts, and arcing) in practice; but that only enables mitigation after a serious electrical issue occurs, rather than preventing it from occurring in the first place. For these reasons the VSST project is focused on developing and advancing methods that enable the diagnosis of precursor fault modes to identify problem areas well before they affect the safe operation of the aircraft.

Chafing and connector degradation are among the most commonly occurring issues identified in wiring health maintenance studies, and both of them are precursors to more serious faults. Past efforts targeted at detecting these faults in practice focused on pairing hardware development with ad-hoc signal processing methods, and failed to produce systems sensitive enough to detect the subtle electrical signatures inherent to these fault modes. Furthermore, prior to NASA's investment in this area there was almost no existing research detailing the underlying physics needed to understand how signals propagating through the interconnect system are affected by these faults, and thus how signals can be used to electronically detect faults in an optimal way.

The funded research in VSST seeks to fill the technology gaps identified above by combining physics-based modeling of electrical signal propagation through chafed wires and degraded connectors with Bayesian probabilistic methods for estimating key faulty system parameters, such as fault location and size, along with a quantitative characterization of the associated estimation uncertainty. The maturation plan for this work is shown in Figure 6.10.

# Technology Migration



**Physics Based Modeling**
- Trade-space analysis and requirements definition
- Possible discovery of new approaches
- Improve EWIS design for fault detectability
- Optimal fault detection algorithms

Now

TRL3

2013

Design for the future

Improve safety in existing aircraft

**Test-bed Development**
- Fault detection on an active shielded twisted pair cable.
- Reconfigurable electrical system for a small aircraft or UAV in the lab

TRL4-5

2015

**Ground Maintenance Tool Development**
- License algorithms to existing tool manufacturers and partners (e.g., Boeing, Livewire Test Labs)
- Help maintainers establish what works in a practical setting

**On-Board Vehicle Health Monitoring**

Figure 6.10.—Chafing and connector diagnostics maturation plan

The completion of this research enables: (1) a complete physics based understanding of the chafing and connector fault detection problem that can lead to improved wiring system design and new alternative methods for fault detection; (2) optimal robust fault detection methods that can account for the effects of real-world uncertainties; and (3) a path to combining wiring diagnostics algorithm outputs with the integrated "whole vehicle" information system described in this document. Ultimately, this work will enable the development of electronically diagnosable wiring systems with greatly improved safety, reliability, and sustainability.

The progress of this task will be evaluated in 1 year increments with the following development to a higher complexity system:

**FY11**: Physics based models for chafing in aircraft wire: Develop and verify computationally efficient physics based models for the time/frequency domain electrical signatures caused by chafing in common shielded aircraft wire types.

**FY12**: Optimal probabilistic fault detection algorithms: Use the Physics based models to create optimized robust fault detection algorithms for chafing fault detection in common aircraft wiring types and validate with lab measurements.

**FY13**: Determine chafing fault detection trade-space: Explore ability to apply the developed fault detection algorithms in both an on-ground maintenance typesetting as well as an on-board setting involving wires carrying active communication signals. Where possible, use the validated

models to suggest new methods for improving wiring system design and enhancing fault detectability. Investigate optimal reflectometry signal profiles that can maximize the accuracy and minimize the uncertainty of fault parameter estimates.

**FY14**: Test-tool development: The lessons learned and the algorithms developed will be matured for utilization in an early prototype test-tool. Such a tool will be useful for maintenance depot applications. Additionally, the tool development will aid in transitioning to an on-line application for detection and diagnosis. The tool will allow for extended validation and provide opportunities for further enhancement to the algorithms for improving detection and mitigating false positives in realistic scenarios.

**FY15**: Demonstrate fault diagnostics for aircraft systems: To support the project goal of achieving an aircraft-level health management system, incorporate and adapt the developed wiring fault test beds and diagnostics software into an integrated demonstration system or test bed.

### 6.6.4   Propulsion Development and Implementation

### 6.6.4.1   Engine Emerging Discs and Composite Materials Health

This work concentrates on efforts to reduce the initiation of damage in high temperature engine components and to insure that any failures that may occur will be contained without causing secondary damage to the airframe. The desire to continuously increase engine efficiency has driven manufacturers to develop engines that operate at ever higher temperatures. Here, complex chemical deposits are condensed on the surfaces of rotating components resulting in corrosion of the surfaces that can lead to the formation of cracks. To mitigate these corrosion processes, advanced coatings will be developed that can withstand the higher engine operating temperatures while providing a corrosion barrier to the high temperature engine materials. In further attempts to improve aircraft efficiency, the materials used to produce engine casings have been changing for the last decade. The use of composite casings instead of traditional aluminum casings represents a significant weight savings while demonstrating excellent capability in containing ejected components. However, there has been very little study on the sustained performance of these new cases after prolonged use and degradation. To insure continued safe operation of the composite engine cases and to develop improved understanding to assist in the design of more damage resistant cases, test methods to examine how cases performed after aging are being developed.

### 6.6.4.2   High Temperature Propulsion Health Management

The implementation approach associated with Propulsion Health Assurance is continued advancement of sensor and algorithm technology, its integration into diagnostic approaches, and overall system demonstration in engine testing. The approach is to very tightly integrate Smart High Temperature Sensor Systems with advances in Propulsion System Diagnostics and to feed both directly into a continuing series of VIPR tests.

Smart High Temperature Sensor Systems development enables improved implementation of reliable sensor technology in the engine through the use of smart, multiparameter sensors and

sensor systems capable of high temperature operation. This task will develop: (1) Multiparameter harsh environment engine sensor suite for comprehensive detection of compressor, turbine, and rotor failure precursors. (2) Harsh environment emission sensor system for overall engine heath evaluation and detection of failures such as oil leaks or engine fires. (3) High temperature wireless sensor system including sensing, electronics, telemetry and power. An example of development path is smart high temperature wireless with integrated electronics. In FY13, demonstration of core capabilities of a wireless smart sensor system in a laboratory setting will take place to establish the building blocks for an integrated system. In FY16, the first engine demonstration of a limited smart high temperature wireless data sensor system to detect engine faults is planned with operation at temperature of at least 500 °C. High temperature wireless is a building block for a new generation of high temperature smart sensor systems with improved ability to characterize engine health without wires (a major cause of sensor system failure). Demonstration of these capabilities is a paradigm shift in on-engine sensor systems enabling revolutionary new capabilities.

Propulsion System Diagnostics enables improved diagnostics both onboard and for later ground-based evaluation. This Task will develop and mature on-board model-based aircraft engine estimation and diagnostic technology by: (1) Focusing on the reduction of safety-significant propulsion malfunctions that have contributed to past propulsion system malfunction plus inappropriate crew response accidents such as asymmetric thrust, rejected takeoffs, and in-flight engine shutdowns. (2) Real-time propulsion state assessment to reduce LOC events and to improve operator situational awareness. (3) Real-time engine performance assessments to diagnosis environmentally induced propulsion malfunctions such as volcanic ash ingestion and engine ice accretion. (4) Providing diagnostic benchmarking problems and metrics leading the engine community in standard approaches and practices. An example of this work is a real-time simulation facility demonstration of asymmetric thrust detection. Asymmetric thrust is a significant contributor to propulsion system malfunction plus inappropriate crew response accidents and incidents. This effort will evaluate the effectiveness of different approaches for the real-time detection of asymmetric thrust conditions.

In future VIPR testing, a suite of advanced aircraft engine health management sensors and algorithms will be evaluated for their capability to improve aircraft engine health assessments. These evaluations are to be conducted through a series of on-wing ground-based engine tests on a high bypass turbofan engine installed on an aircraft. Engine test scenarios for VIPR Tests include nominal operating scenarios, non-damaging seeded fault scenarios, and damaging fault scenarios such as sand and volcanic ash ingestion tests. Propulsion health management technologies to be evaluated during this testing include microwave tip clearance sensors, chemical emissions sensors, oil debris/condition monitoring sensors, high frequency accelerometers, electrostatic debris monitoring sensors, and gas path performance diagnostic algorithms. Such simulated and seeded engine tests are rare and vital in validation of sensing and diagnostic technologies, and these tests plan to include interaction with OGA and industry. This task directly depends on the development of both new technologies in Propulsion System Diagnostics and Smart High Temperature Systems to expand the capabilities in Propulsion

Health Management and demonstrate new abilities to assess engine health in a range of engine testing conditions that directly address a range of safety issues.

The successful completion of this testing provides new capabilities for engine monitoring; new inputs to engine diagnostics, including those for gas path and turbomachinery; maturation of sensor systems with on-engine testing; and unique correlation of sensor data with engine fault conditions. Results include:

- Evaluation and demonstration of emission sensor systems to identify exhaust gas species and detect changes under varying engine operating and fault conditions in a relevant operating environment.

- Data collection from multiparameter engine sensor systems in both simulated and real fault conditions to assist evaluation of model-based gas-path diagnostics methods

- Evaluation and demonstration of rotordynamic structural health monitoring: Smart accelerometers and blade clearance and tip-timing sensors to monitor the rotating blade and vibrational properties of the engine

The challenge in propulsion information fusion is to develop methods for combining/fusing disparate aircraft engine health information sources to produce an improved assessment of overall engine health. This includes the ability to combine diagnostic information related to different engine subsystems (e.g., combining gas path health and structural health information), which are obtained by applying different diagnostic methods (e.g., combining model-based and data-driven diagnostic approaches) and derived from sensor measurements acquired at different sample rates. The fusion of engine diagnostic information is expected to yield several improvements over segregated diagnostic analysis. This includes reduced diagnostic latency, the detection of smaller magnitude faults, and improved capability to discriminate between different fault types. Examples of diagnostic information fusion include, but are not limited to: 1) combining performance, vibration, and blade health information to diagnose foreign object damage, 2) combining vibration and oil debris health information to diagnoses mechanical component faults; and 3) combining chemical emission and performance health information to diagnose combustion faults.

A summary of the Propulsion Health Milestones showing this integrated approach for technology development is given below and in Figure 6.11.

**FY12:** Demonstrate 1st generation off-nominal engine operation sensing: Correlate 1st generation sensor system responses in VIPR tests to simulated engine faults at a basic level. These sensors include smart diagnostic accelerometer, emissions sensors, and a checkout of the microwave tip clearance sensor operation, and will be correlated with diagnostic modules to better characterize engine health state. These are unique tests that allow the introduction and evaluation of new technology into health management applications.

**FY13:** Demonstrate ability to diagnose off-nominal engine operation: C-17 engine data (both existing data and potential future VIPR test data) will be processed through the model-based diagnostic architecture. This will demonstrate the diagnostic functionality of the model-based gas path diagnostic architecture. This includes the architecture's ability to: 1) "self-tune" to match the performance of the actual engine; and 2) diagnose the occurrence of any inserted gas path fault conditions.

**FY14:** Demonstrate engine failure detection and diagnosis with expanded sensor suite that includes sensors installed in core of engine: Correlate 2nd generation sensor system responses in VIPR tests to simulated and real engine faults. Building on the first generation sensor systems previously demonstrated (smart diagnostic accelerometer and emissions sensor systems), expand the sensor suite demonstrated on-engine to include candidate technologies such as the microwave tip clearance sensor, high temperature pressure sensor, thin film physical sensors, fiber optic temperature sensors, and limited high temperature electronics.

**FY15:** 1) Complete sensor diagnostic functions for previously tested fault conditions: Each sensor is sensitive to a certain subset of faults that will have been seeded in the first series of engine tests. Completion of this analysis will allow for new sensing capability to augment the existing gas path and structural diagnostic systems. These sensor elements are candidates for integration into the next generation high temperature smart sensor systems. 2) Demonstrate engine diagnostic systems based on expanded sensor suite: Potential data sets include test data collected from VIPR I, II, and III testing. This will demonstrate the diagnostic and performance estimation functionality of the model-based gas path diagnostic architecture. Additionally, the improvements gained by incorporating additional gas path sensor measurements will be evaluated. This is a major step in moving toward the capability to provide in-flight capabilities to diagnose engine health state and prevent in-flight propulsion malfunctions.

**FY16:** Develop propulsion health assessment system: Design and develop a modular, hierarchical, propulsion health management system to enable the fusion of diagnostic information produced by different propulsion diagnostic subsystems. This is the product integration of the sensors and diagnostics activities matured in the first 5 years of MVS, and includes new sensor systems and diagnostics evaluated in on-engine testing.
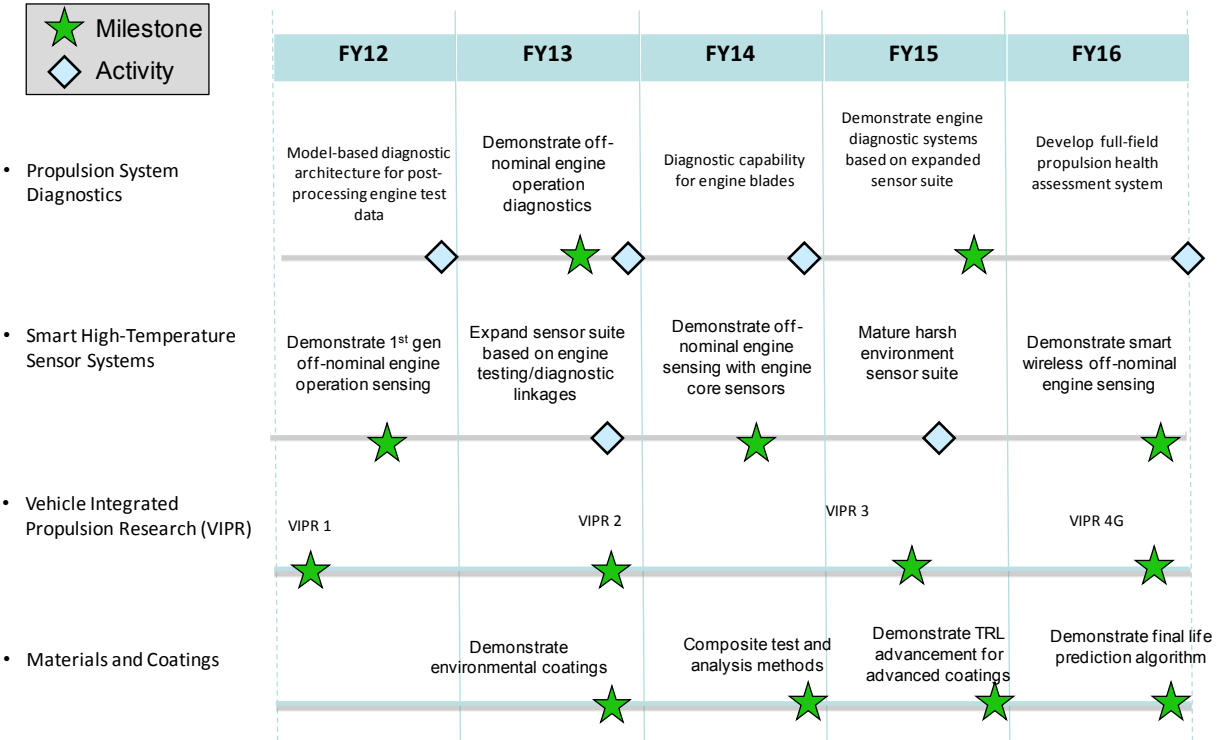
Figure 6.11.—Propulsion Health Assurance milestones and activities.

## 7.0    Possible System Benefits

The IVHAS concept presented in this document holds multiple benefits. First and foremost, the intended benefit of IVHAS is improved aviation safety. However, it is readily acknowledged that without associated economic benefits it is difficult to field new technology. Therefore, in addition to safety benefits IVHAS must also provide an economic benefit that enables the technology to "buy its way" into implementation. Expected economic benefits include: reduced in-flight malfunctions, reduced unplanned maintenance, reduced unscheduled part replacements, and reduced maintenance related delays and cancellations. For example, a fundamental change in maintenance approaches from maintenance on schedule to condition-based maintenance may have a notable economic impact. Further, many of the resultant IVHAS benefits come from taking a system-level approach to assuring vehicle health. This includes design enhancements to prevent or mitigate system failures, advanced sensing techniques to measure new parameters/locations, automated monitoring and analysis (both on-board and off-board), enhanced manual inspection techniques, and the sharing and integration of information amongst subsystems.

Initially, much of the VSST MVS work will focus on subsystem technology development and maturation. This includes developing improved materials and coatings, algorithms, sensors, and inspection techniques. The focus will be on the health assurance challenges presented by emerging designs, harsh operating environments, difficult to inspect locations, and the need to leverage all available information sources (both on-board and off-board). Individually, advancements in any one of these areas could be critical in breaking the chain of events leading to an aviation accident. Collectively, these technology advancements enable safer and more efficient aircraft operation and sustainment. Moving forward, the integration of these technologies holds further benefits. Understanding the health assurance challenges presented by emerging materials and designs enables the appropriate monitoring, inspection, and fault mitigating strategies for these technologies to be developed. Also, the interaction and sharing of information between subsystems provides improved vehicle health assurance capabilities. The techniques to share and analyze vehicle health information between vehicle information systems (both on-board and ground-based), fleet-wide databases, ground maintenance personnel, overhaul facilities, and fleet managers enables the efficient and effective management of system health, maintenance actions, and cost. For example, on-board health monitoring functionality is designed to identify system anomalies in-flight, which can be autonomously communicated to ground maintenance personnel and used to optimally schedule the maintenance/inspection actions necessary to safely return the vehicle to service with minimal impact to flight operations. Additionally, maintainers are provided access to a fleet-wide central database of vehicle operating history and health information that assists them with fleet logistic decisions, including the capability to quickly identify and address maintenance/inspection related needs. The judicious sharing of select vehicle health state information to support crew decision making and mitigate/avoid loss of control scenarios can further help to enhance aviation safety.

Integrated Vehicle Health Assurance benefits include on a broad level:

- Overall vehicle health assessment. Vehicle state information during standard conditions and adverse events to assess individual and combined health of vehicle subsystems

- Subsystem methods/information for prediction of future health/extend life

- Subsystem health assessment addresses Vehicle Health Assurance but also Loss of Control and Effective Crew-System Interactions.

- For example, processing of the data from a particular sensor reveals the need for a maintenance action, which can then be autonomously coordinated in advance with a maintenance facility and optimally scheduled to minimize impact to operations.

- Maintainers interface with central database through custom applications that help them quickly locate and fix problems according to a preset schedule.

- Fleet managers can monitor overall system health, maintenance actions, and cost.

The vision for an Integrated Vehicle Health Assurance System is to provide an integration of design and materials, onboard monitoring, and ground-based maintenance functionality to assure overall vehicle health. This includes providing vehicle health state information for use in loss of control, crew system interfaces, and maintaining vehicle safety between inspections. In other words:

- Advanced materials and coatings prevent unsafe damage growth between inspections in areas difficult to inspect

- Enhanced inspection methods increase ability to detect damage and faults during inspections

- On-board detection identifies damage or post-inspection faults, provides information on the fault, and provides alerts that corrective maintenance is required.

To illustrate the application of our approach, two examples are given below. These examples are chosen to highlight the concept that changes in the vehicle health state can occur after a major inspection. One of the most straightforward ways to do this is to examine damages that occur to a vehicle while in-flight. Thus, examples related to environmental hazards are discussed. While aspects of environmental hazards are addressed elsewhere in the Aviation Safety Program, response to these environmental hazards on the vehicle level is a major responsibility of the MVS Technical Challenge. A vision of the MVS Technical Challenge response is given below.

## 7.1 Vehicle Damage Due to Lightning Strikes

### 7.1.1 Scenario

After a major inspection, the vehicle is struck by lightning while in-flight. The vehicle itself has significant composite components that are more susceptible to damage than traditional metallic systems. It is assumed that the lightning strike can be detected, but the extent of the damage due to this lightning strike is unknown to the crew. The following describes how an IVHAS can prevent the crew from improperly responding to this event, and how to keep such an event from becoming hazardous in the first place.

### 7.1.2 IVHAS Response

Preparing for such an incident should not begin after it happens. Rather, it is generally known that composite materials have different aging properties and response to damage. Making these materials resistant to in-flight damage by design is the first step towards ensuring continued flight safety. IVHAS will not only study the properties of composite materials related to response to damage, but also provide for a limited amount of self-healing.

If the lightning strike is major and causes notable damage to the aircraft, a number of systems may be affected depending upon where the lightning strike takes place. The composite structure could be damaged with significant consequences especially near the fuel tank. The engine could be damaged either causing structural damage to the engine itself, or causing failures of the one or more engine subsystems. Finally, the electrical system could be damaged either exposing wires or disconnecting wires altogether leaving some control functions inoperable.

IVHAS in the form of DAASH provides structural health monitoring integrated across the vehicle structure. Detection and identification of the structural damage location and magnitude is the first step towards an understanding of what has happened to the vehicle. Verification and identification of any engine damage would be another step towards confirming continued flight safety. Isolation of wiring faults and any discontinuity in avionics functions both corroborates the identification of the lightning strike location, but also provides information on any resulting lack of system functionality important to recovering enough control of the vehicle to execute a safe emergency landing if necessary.

The IVHAS approach minimizes overall burden to the vehicle by locally processing this information to determine the state for each subsystem. The assessment for each subsystem is based upon the "fingerprint" of the vehicle. That is, an understanding of whether damage has occurred needs to be based on such factors as the current baseline and history for the relevant individual vehicle subsystems. For example, it's important to account for affected components near the end of their maintenance life spans, or with histories of borderline functionality.

The information from these three subsystems is then fed into a Vehicle Level Reasoner (VLR). This Vehicle Level Reasoner is the arbitrator in assessing the vehicle health state given the various inputs. Since local processing is done within the subsystems, only higher-level information is fed to the VLR on a standard basis. If a fault is identified, then the VLR can query

the individual subsystems for more detailed information to determine the overall vehicle health state. The VLR consolidates this information to determine the health state of the system in-flight.

A fundamental point associated with the VLR is that it does not provide information directly to the crew. If the damage is considered imminently hazardous, then the information is fed through proper CDM and/or ASC methods to determine the proper response and presentation to the crew when necessary. In parallel, condensed information can be transmitted to the ground to provide alert of the hazard enabling the maintenance facilities, or emergency response teams to immediately address the problem on landing.

If the lightning strike is minor and causes minimal damage to the aircraft during this particular flight, it does not mean that this damage will not pose a safety hazard in future flights. For example, the lightning may produce a small crack within the composite structure that could grow over time into more significant damage that affects vehicle operation. The lightning strike may damage the structure of the engine causing an oil leak that compromises future engine performance or affects the quality of bleed air provided to the air cabin environment. Finally, the lightning strike could affect the avionic system causing localized heating to a wire, which upon further chafing could result in an avionics malfunction or even a fire.

Although the level of damage may not be enough to immediately affect the safety of the vehicle, it probably will be a cause for maintenance action. The VLR and each subsystem can locally process and record the incident and the change in fingerprint of the vehicle. Upon landing, a hierarchy of messaging can be provided to the ground maintenance crew. This set of messaging can include notification that a lightning event has occurred, or simply be notification that the lifetime of an individual part is nearing its limit due to off nominal conditions that have occurred during the vehicle's operation.

In this example, the IVHAS can record that indeed a lightning strike has taken place and provide information related to its likely location. Enhanced inspection techniques related to composite materials can then examine the relevant parts of the structure. These enhanced inspection techniques will be able to identify flaws, which may have been either insignificant or nonexistent for metallic structures, but could be the source of long-term degradation for composite structures. The detected presence of an oil leak or other engine malfunction can allow grounds crews to isolate those components for further evaluation. If the electrical system were damaged, maintenance crews would know where to follow up with an inspection and make the needed repairs.

Thus, in order to Maintain Vehicle Safety between inspections in this particular example of a lightning strike, it is not just a single subsystem that provides relevant information. Nor is it only in-flight data that is used to assure vehicle health. It is the combination of materials, in-flight monitoring, and enhanced inspection techniques and vehicle prior history that provides a framework for long-term vehicle safety.

## 7.2 Vehicle Damage Due to Volcanic Ash

### 7.2.1 Scenario

In contrast to the lightning strike example, the potential hazard due to volcanic ash may not be easily identifiable by the crew. Volcanic ash is often transparent to the crew and its presence may not be predicted beforehand by air traffic control. Presently, there may be little indication that the vehicle is affected by volcanic ash until significant system damage occurs. For example, engine damage due to volcanic ash ingestion may occur within minutes. Indications of impingement of particulates upon the airframe may be noticed, but without correlation to other indicators may be misinterpreted. The following describes how the technologies being developed in IVHAS can impact this safety hazard.

### 7.2.2 IVHAS Response

Damage caused by a series of small particulate strikes may in fact be more significant for composite materials than present metallic structures. Small indentations in composite structures have different growth properties than what might be seen in metallic structure, and can potentially grow into more serious damage conditions. Thus, damage tolerant material designs are critical to maintaining safe operation. Further, self-healing composite materials may eliminate the need for repairs associated with minor damage and even prevent long-term safety issues from occurring later in the vehicles life.

As in the previous example, IVHAS in the form of DAASH provides structural health monitoring integrated across the vehicle structure. Detection of the structural damage location and magnitude is an indicator that the aircraft is experiencing conditions beyond standard operation. While diagnostics and prognostics of changes in the aircraft structure is processed locally, summary information related to changes in the airframe fingerprint can be provided to the VLR.

Engine damage associated with volcanic ash is presently not fully understood. The activities in IVHAS are aimed at significantly improving the understanding of the effects of volcanic ash on engine systems through the series of VIPR tests discussed above. These activities will also provide new sensor systems to better characterize the overall engine state. For example, if conducted as planned, exposure to volcanic ash over a period of time will be correlated to both existing and new sensor measurements. After the testing has driven the engine to failure, post failure diagnostics will look at the causes of engine failure. This information can be fed into improved engine sensor systems, but also be valuable towards the development of relevant engine diagnostic systems.

Onboard engine sensors and diagnostics are critical to being able to detect a hazardous event such as damage caused by volcanic ash. New engine sensor systems are tools that if implemented can provide new information on changes in engine temperature profile, tip clearance to monitor depositions on blades, improved accelerometers to detect the onset of changes in vibration conditions, and bleed air and emission sensor systems to monitor changes in the other aspects of engine operation. Onboard engine diagnostics is fundamental to correlating these various inputs

into an assessment of changes in engine state and potential hazardous conditions. This engine diagnostics approach, which takes into account the particular fingerprint of the engine while on board, is a core feature to providing alerts regarding changing engine conditions in a real-time basis.

The information from the airframe and propulsion subsystem can be then be fed into the VLR for a more integrated understanding of the vehicle health state. Correlation between the airframe and propulsion subsystem information can provide an indication related to the source of the problem. If for example, an engine failure begins to occur and limited airframe impact is noted, then such a condition may indicate the presence of volcanic ash. In contrast, if a more significant impact is noted in correlation to changes in engine operation, other factors may be occurring, such as a bird strike.

The role of the VLR in this case is again to provide information to other aircraft and ground systems. If the damage is considered imminently hazardous, then this information can be fed to the CDM and ASC methods for proper response or presentation to the crew. In the case of volcanic ash, a priority system may need to be established to highlight high levels of hazard. Regardless, this information is not directly provided to the crew. However, indications that an aircraft is being exposed to volcanic ash is of high interest to ground personnel. Such indications correlated across multiple aircraft can provide air traffic managers with an alert that volcanic ash may be present in the region assisting in fleet-wide safety.

IVHAS that can indicate that an aircraft has potentially been exposed to volcanic ash can enable ground personnel to provide appropriate maintenance actions. In fact, given the data produced by the VIPR series of tests, ground personnel will have an improved understanding of what specialized inspections may be necessary for systems exposed to volcanic ash. Enhanced inspection techniques related to composite materials can identify flaws, which may have been either insignificant or nonexistent for metallic structures, but could be the source of long-term degradation for composite structures.

Thus, in order to Maintain Vehicle Safety between inspections in the case of volcanic ash exposure while in-flight, correlation of information from at least two subsystems can provide an indication of the potential hazardous condition. The crew may not be aware of such a volcanic ash exposure, and thus not be able to notify ground maintenance. This is an example where in-flight data from multiple subsystems generates relevant maintenance actions related to what the aircraft has experienced in-flight, as opposed to being determined by a preset schedule. As in the previous example, it is the combination of materials, in-flight monitoring, and enhanced inspection techniques and vehicle prior history that provides a framework for long-term vehicle safety.

## 7.3 Maintenance Issues Leading to a Sequence of Events

### 7.3.1 Scenario

A series of maintenance issues, combined with an unexpected atmospheric disturbance, leads to a single system failure that cascades to affect multiple subsystems endangering the safety of the

overall vehicle. This scenario includes actions by the pilot that further complicate the ability to maintain vehicle safety. The vehicle itself has a mixture of metallic and composite components. The following describes how an IVHAS system can help prevent the scenario from escalating into an in-flight failure, and in the event that an in-flight failure does occur, assist the crew and control system in responding to the event.

## 7.3.2   IVHAS Response

This scenario concentrates on maintenance and design issues that then lead to a single system failure that cascades to affect multiple subsystems endangering the safety of the overall vehicle. This scenario contains examples of multiple maintenance issues that combined with atmospheric conditions and crew response lead to a hazardous condition. While the probability of all these issues occurring at the same time as low, any one of these can cause an accident or incident.

This safety hazard begins with known faulty accelerometer that was not replaced in the inertial reference unit. During an atmospheric disturbance, a second accelerometer in the inertial reference unit also fails leading to the aircraft flight computer to cause the aircraft to pitch up based on faulty information. The pilot attempts to respond to the misunderstanding of the flight situation with aggressive use of control surfaces leading to structural failure. The structural failure is in part due to excessive fatigue of the flight control surfaces as well as their operation beyond standard operating conditions. This includes damage in composite materials not detected during inspection. The following discusses each of these steps that led to the hazardous condition, and then describes a possible response of IVHAS even if this series of events occurs.

A major component of IVHAS is the concept that a "fingerprint" of the vehicle is available throughout its operation. In order for such a fingerprint to be valid, storing and processing of information is necessary. This data processing and analysis will be performed not just in a central location, but at various levels throughout the vehicle system and ground support operations. Maintenance actions performed on the vehicle should be included as part of the vehicle fingerprint. Such maintenance history can include the identification of parts that have been replaced due for maintenance, or have typically been considered in proper operating condition. Such a fingerprint should certainly include record of a part identified as faulty. Such data can be recorded, especially simple flagged data, as part of information carried with the vehicle and updated while on the ground. If a specific set of maintenance data is not included as part of the vehicle fingerprint, targeted data sets can be transmitted to the vehicle if the situation warrants it.

However, there is a limit to the amount of data that can either be transmitted or stored. The IVHAS is based on a hierarchal approach where intelligence is distributed throughout the vehicle down to the level of smart sensor systems and components. A smart sensor will determine its own health and flag that information as a standard part of the data stream. A local node can take this into account when comparing various sensors, for example, three accelerometers, in a voting scheme. In the case of the known faulty accelerometer that was not replaced, the approach is that the accelerometer itself should evaluate its health and identify its data as suspect. MVS is in fact developing such a smart accelerometer. Thus, the implementation of a distributed intelligence approach can contribute in not only identifying that the first accelerometer is faulty, but also that

the second accelerometer has also failed. The information then provided from the local node does not need to include all of the information from both accelerometers. Rather, the local node simply reports two failed accelerometers, and the information from the remaining operational sensor.

If inaccurate information is supplied to inertial reference unit, the overall health state of the vehicle can be understood by monitoring and correlating sensed information throughout the vehicle. For example, measurement of the strain on the airframe can provide independent information on the flight environment of the vehicle. The initial atmospheric disturbance would be expected to have an effect on the airframe, which would subside as the disturbance passes. Thereafter, the strain on the vehicle produced by external factors would then be associated with the flight conditions present after the disturbance. Effectively, being hit with air turbulence would be something that could be determined with a structural health monitoring system, and provide information both on the duration and the extent of the turbulence.

If the pilot is unaware of the actual situation and begins to attempt to establish control through aggressive use of the flight control surfaces, then the aircraft may be operated beyond standard limits. In this scenario, fatigue has occurred associated with a flight control surface at a much faster rate than normal. In this case as well, distributed intelligence can have a significant role to play in maintaining vehicle safety. If the system can perform self diagnostics, then a history of this flight control surface loading and dynamics can be maintained. If it is determined that a failure is imminent, then the subsystem can also provide information to a local node for processing. If aggressive flight control maneuvers taken by the pilot subject the vehicle's flight control surfaces to unsafe levels of loading and fatigue, then the airframe structural health monitoring system can give warning of excessive use of the control surfaces before failure occurs.

The integration of advanced design and an understanding of the material properties are crucial in both understanding the status of the vehicle and remaining life in structures that are operating beyond their design limits. These faults may occur at different rates for different material components. Although there is a significant history related to metallic systems, the information available related to composite materials significantly less comprehensive. In this scenario, improved inspection techniques found structural faults that previously would have been undetected. Monitoring systems onboard the aircraft can identify regions in particular where more extensive inspection is necessary, and identify areas whether excessive wear has occurred. This inspection information, combined with onboard detection systems, becomes part of the fingerprint of the vehicle to be used both to maintain vehicle operational condition but also in cases if unforeseen factors have caused structural damage.

The failure of flight control surfaces on an airframe can be catastrophic. If such failure occurs, it is first important to understand what has failed. If structural failure is beginning to occur, this can affect other parts of the vehicle. In principle, a cascade effect can result affecting the airframe and propulsion subsystems, or even disrupt the avionic subsystem. The combination of the health and status information related to the airframe and avionics subsystems can be used to determine

the status of the overall vehicle. A Vehicle Level Diagnostics System can be used to correlate the information between the various subsystems providing an overall assessment of the vehicles health. Even an incomplete snapshot the vehicle health can be critical; understanding, for example, if a rudder has broken off or is still in place but inoperable is a notable component in understanding what has happened to the vehicle. This information can then be provided to both CDM and ASC to determine potential courses of action.

Past NASA studies have shown, that in the event of some flight control system failures it is possible to use the aircraft engines to avert or recover from the scenario [199,200]. Such approaches are presently being pursued in ACS. However, such mitigation strategies may require operation of the engine systems significantly outside of standard operating envelope. As noted elsewhere in this scenario, operation outside of standard conditions can be problematic if this then causes further system failure. It is then important to understand engine health in an ongoing basis if they are to be used also as a control effector for the vehicle. A focus of the IVHAS activities is to develop and demonstrate harsh environment smart sensor systems combined with propulsion system diagnostics and performance monitoring. These harsh environment smart sensor systems not only provide measurements previously unavailable, but also, as noted above, are able to identify their own health status. The propulsion system diagnostics combined with the sensor systems for real-time propulsion state assessment can improve operator situational awareness and provide an ability to determine remaining life and operability limits of the engines. In particular, this remaining life is foundational to approaches that involve the use of engines as the primary method of vehicle control.

Thus, in order to Maintain Vehicle Safety in this scenario, it is important to keep the chain of events from occurring that lead to a hazardous condition. This begins with improved maintenance techniques and data handling that identifies sensor, component, or subsystem faults before they can lead to a serious condition. This is not isolated in one part of the vehicle, but system faults in one part of the vehicle can cascade towards a vehicle level affect. A fingerprint of the vehicle combined with distributed intelligence throughout the system can both prevent hazardous conditions from occurring and allow a better understanding of the vehicle status if a fault has occurred. This information can be provided to ASC and CDM to allow more appropriate response to the situation. It is the combination of materials, enhanced inspection techniques, in-flight monitoring, vehicle prior history, and now combined with control systems and crew interfaces that provides a framework for long-term vehicle safety.

## 8.0   Longer Term IVHAS Vision

A longer term vision for Vehicle Health Assurance is shown in Figure 8.1. It is an expansion of the Concept of MVS Integrated Vehicle Health Assurance shown in Figure 6.4 that is advanced by concepts and developments discussed in Sections 6.5 and 6.6. However, the long-term concept of Figure 8.1 goes beyond what is needed for the MVS IVHAS approach to even more integrated intelligence into a vehicle. This long-term vision can be described as bringing together an ability for Robust Design, Maintaining and Sustaining the vehicle systems, and Vehicle Health Assessment.
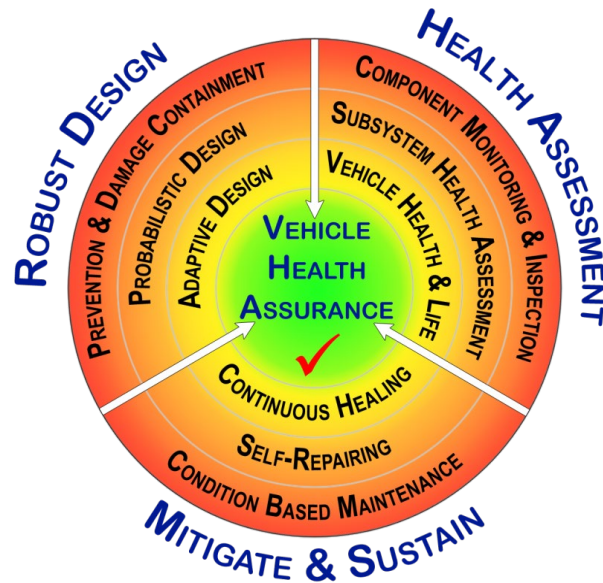
Figure 8.1.—A long-term vision for Vehicle Health Assurance.

Robust Design within the next several years will concentrate on damage prevention and containment. However, as materials models improve, designs based on probabilistic design approaches can be envisioned that involve a high level of prognostic capability to reduce the design margin now typically used for safety purposes, and thus optimize system configuration for a better understanding of what is actually needed for a flight system. The ideal realization of robust design is an adaptive design that is self-configurable, i.e., able to modify its configuration to changes in both external hazards and damage, as well as component failures, at least until the aircraft is safely on the ground.

The capability to Maintain and Sustain the vehicle first moves beyond the approach of maintenance by schedule presently used to one based on the condition of the component, subsystem, or vehicle. The first step beyond external condition based maintenance is a system that is internally self-repairing. A simple version of this approach is now being addressed with basic self-healing materials but advances the approach towards self-repairing systems that address vehicle faults autonomously. A long-term goal is an adaptive vehicle that is in a continuous process of healing and modifying its configuration for safety and performance optimization.

Health Assessment in the nearer future will concentrate on component and subsystem health monitoring and more advanced methods of inspection. The coupling of both on-board sensors with off-board inspection systems to complement each other providing for more complete monitoring is part of improved vehicle awareness in the next several years. These hardware approaches must be coupled with software approaches for diagnostic and prognostic evaluation of the component and subsystem, moving towards an overall vehicle health assessment approach. Ideally, this complete vehicle health assessment system also includes the ability to predict the remaining life of components, subsystems, and finally the overall vehicle.

A long-term vision of Vehicle Health Assurance combines all three capabilities; the adaptable design approach needed to have a proper understanding of the vehicle health state and life, with a capability to self-configure and adjust. The overall approach is for an intelligent and autonomously safe vehicle that is self-monitoring, self-correcting and repairing, and self-modifying [158]. One approach towards this vision is to build the intelligent system bottom-up from smart components. These smart components are independently self-monitoring, self-correcting, and self-modifying. Smart components monitor and adapt their individual status to the mission objectives and local conditions. Information is communicated to local nodes and the collection of these smart nodes encompasses the overall vehicle level operation. Overall, the approach is self-aware components yielding a self-aware vehicle system.

It should be emphasized that this vision is meant as a guide for long term development and not part of MVS in the next 5 years. Parts of this work may be addressed over time by other NASA programs and projects such as Fundamental Aeronautics, Aeronautical Sciences, as well as in the Aviation Safety program and by OGAs. While the foundation for such a vision is being laid in the MVS Technical Challenge, the objectives of the MVS Technical Challenge is targeted towards impact in the next 5 years as described elsewhere in this document. Nonetheless, the vision of a system that, like a biological system, can know its environment, process information, communicate, and adapt, i.e., a system that can evaluate and fix it itself, while being able to get external help as needed (go to the doctor) can be suggested as a goal in long-term safety advancements.

# Appendix A.—Acronyms

| | |
|---|---|
| ACARS | Aircraft Communications Addressing and Reporting System |
| ADEPT | All-Domain Execution and Planning Technology |
| AEPHM | Aircraft Electrical Power Systems Prognostics and Health Management |
| AEST | Atmospheric Environment Safety Technologies |
| AFRL | Air Force Research Lab |
| AIL | Aircraft-In-the-Loop |
| ASC | Assure Safe and Effective Aircraft Control under Hazardous Conditions |
| ASIC | Application Specific Integrated Circuit |
| ARMD | Aeronautics Research Mission Directorate |
| BITE | Built-in Test Equipment |
| BVID | Barely Visible Impact Damage |
| CAA | Civil Aviation Authority |
| CAST/ICAO | Commercial Aircraft Safety Team/International Civil Aviation Organization |
| CDM | Improve Crew Decision-Making and Response in Complex Situations |
| C-MAPSS | Commercial Modular Aero-Propulsion System Simulation |
| C-MAPSS40k | Commercial Modular Aero-Propulsion System Simulation, 40,000 lb |
| ConOps | Concept of Operations |
| DAASH | Dynamic Assessment of Aircraft Structural Health |
| AEST | Atmospheric Environment Safety Technologies |
| EHM | Engine Health Management |
| EHA | Electrohydraulic Actuators |
| EMA | Electromechanical Actuators |
| EMS | Engine Monitoring System |
| EWIS | Electrical Wiring and Interconnect System |
| FAA | Federal Aviation Administration |
| FADEC | Full-Authority Digital Engine Control |
| FAR | Federal Aviation Regulations (FAR) |
| FDAMS | Flight Data Acquisition Management System |
| DFADU | Digital Flight Data Acquisition Unit |
| FDR | Frequency Domain Reflectometry |
| FOD | Foreign Object Debris |
| FY | Fiscal Year |
| GPHM | Gas Path Health Management |
| ICR | Inappropriate Crew Response |
| HIL | Hardware-In-the-Loop |
| HPC | High Pressure Compressor |

| | |
|---|---|
| HCF | High Cycle Fatigue |
| HPT | High Pressure Turbine |
| HUMS | Health and Usage Monitoring Systems |
| IFSD | In-Flight Engine Shutdown |
| IVHAS | Integrated Vehicle Health Assurance System |
| IVHM | Integrated Vehicle Health Management |
| JPDO | Joint Planning and Development Office |
| LEHV | Low Energy High Voltage |
| LOC | Loss of Control |
| LRU | Line Replaceable Unit |
| MOSFET | Metal Oxide Field Effect Transistor |
| MVS | Maintaining Vehicle Safety |
| NDE | Non-Destructive Evaluation |
| NDI | Non-Destructive Inspection |
| NASA | National Aeronautics and Space Administration |
| NASSP | National Aviation Safety Strategic Plan |
| NAVAIR | Naval Air Systems Command |
| NextGen | Next Generation Air Transportation System |
| NTSB | National Transportation Safety Board |
| OGA | Other Government Agencies |
| OEM | *Original Equipment Manufacturer* |
| PASD | Pulse Arrested Static Discharge |
| PSM | Propulsion System Malfunction |
| SHM | Structural Health Monitoring |
| SBIR | Small Business Innovative Research |
| SOA | State-Of-The-Art |
| SSTDR | Spread-Spectrum Time Domain Reflectometry |
| TC | Technical Challenge Problem |
| TDR | Time Domain Reflectometry |
| UAV | Unmanned Aerial Vehicles |
| UER | Unscheduled Engine Removal |
| USAF | United States Air Force |
| VSST | Vehicle Systems Safety Technologies |

# References

1. *A380 wings to be checked for cracks, EASA says* in BBC News January 20 2012. http://www.bbc.co.uk/news/business-16649334.

2 Incident description , http://aviation-safety.net/database/record.php?id=20050801-1

3. "Global Fatal Accident Review 1997-2006," CAP 776, (July 21 2008), Civil Aviation Authority, Safety Regulation Group.

4. Jones, S.M., Reveley, M.S., Withrow, C., Evans, J.K., Barr, L.C., and Leone, K. "Systems Analysis of NASA Aviation Safety Program - Final Report," (June 2010).

5. Antón, P.S., Ecola, L., and Kallimani, J.G., *Advancing Aeronautics: A Decision Framework for Selecting Research Agendas*. 2011: Rand Corporation: Infrastructure, Safety, and Environment and National Security Research Division.

6. Tiffany, C.F., Gallagher, J.P., and Babish, C.A. "Threats to Aircraft Structural Safety, Including a Compendium of Selected Structural Accidents/Incidents," (March 2010), Aeronautical Systems Center Engineering Directorate.

7. Babish, C.A. IV, "USAF ASIP: Protecting Safety for 50 Years," 2008 ASIP conference, San Antonio, TX, 2 Dec 2008.

8. *Lessons Learned From Transport Airplane Accidents*. Accident Threat Categories, Structural Failure 2012; Available from: http://accidents-ll.faa.gov/ll_main.cfm?TabID=3.

9. McIver, K. "Aging Aircraft and Durability System Level Concepts for Airframe Airworthiness Management," NNL10AB23T, in Final Report Task Order Agreement (2011), The Boeing Company.

10. *In-flight breakup over the Atlantic Ocean, Trans World Airlines Flight 800 Boeing 747-131, N93119, near East Moriches, New York, July 17, 1996*. DIANE Publishing.

11. "Aviation Investigation Report: In-Flight Fire Leading to Collision with Water Swissair Transport Limited ," A98H0003, (September 2 1998), Transportation Safety Board of Canada.

12. Evans, D., *Safety: Cruising With Smoke* in Avionics Today, 2003.

13. *Potential In-Flight Fire Events Occur Daily; Many in Inaccessible Areas* in Air Safety Week April 2000.

14. Wheeler, K.R., Timucin, D.A., Twombly, I.X., Goebel, K.F., and Wysocki, P.F. "Aging Aircraft Wiring Fault Detection Survey," (June 1 2007), NASA Ames Research Center.

15. Smith, C. "Transport Aircraft Intrusive Inspection Project," (December 29 2000), Aging Transport Systems Rulemaking Advisory Committee (ATSRAC).

16. *Enhanced Airworthiness Program for Airplane Systems/Fuel Tank Safety (EAPAS/FTS)*. Federal Register, 2005. **70** (193): p. 58508-58561.

17. Service difficulty reporting database: http://av-info.faa.gov/sdrx/.

18. Yearwood, B. "Non-destructive inspection (NDI) technology for aircraft wire harness chafe & damage detection," Aircraft Airworthiness & Sustainment Conference, April 2011.

19. Balaban, E., Saxena, A., Bansal, P., Goebel, K.F., Stoelting, P., and Curran, S. A. "Diagnostic Approach for Electro-Mechanical Actuators in Aerospace Systems" in *IEEE Aerospace Conference*. 2009.

20. http://www.ntsb.gov/investigations/summary/AAR0201.html

21. Vutetakis, D.G. and Viswanathan, V.V. "Determining the state-of-health of maintenance-free aircraft batteries" in *Battery Conference on Applications and Advances, 1995., Proceedings of the Tenth Annual*. January 10-13 1995.

22. Bharadwaj, R. and Biswas, G. "Avionics Diagnostics and Prognostics Using Hybrid Bond Graphs," (2011), Honeywell and Vanderbilt University.

23. *Uncontained Turbine Engine Rotor Events: Data Period 1984 Through 1989*. 1998, Warrendale, PA: Society of Automotive Engineers.

24. Clark, S.T., Iverson, R.E., Mumaw, R.J., Sikora, J.A., Vian, J.L., and Winters, V.J. "Indications of Propulsion System Malfunctions," (2004), U.S. Department of Transportation, Federal Aviation Administration.

25. Clark, S., Ostrom, G.B., and Clark, S.C. "Engine Damage-Related Propulsion System Malfunctions," DOT-FAA-AR-08-24, (December 2008).

26. Stange, W., " Instrumentation Needs to Reduce Turbine Engine Related Class A Mishaps Within the USAF" in ISA 53rd International Instrumentation Symposium. April 30-May 3 2007. Tulsa, OK.

27. Behbahani, A.R. "Need For Robust Sensors For Inherently Fail-Safe Gas Turbine Engine Controls, Monitoring, and Prognostics" in *52nd International Instrumentation Symposium*. May 7-11 2006. Cleveland, OH.

28. Hunter, G. W. and Behbahani, A. "A Brief Review of the Need for Robust Smart Wireless Sensor Systems for Future Propulsion Systems, Distributed Engine Controls, and Propulsion Health Management," Proceeding of the 58th International Instrumentation Symposium, Hyatt Regency La Jolla, San Diego, California, 4–7 June 2012

29. Ramohalli, G. "The Honeywell on-board diagnostic and maintenance system for the Boeing 777" in *IEEE/AIAA 11th Digital Avionics Systems Conference*. October 5-8 1992.

30. *Operational Performance Brochure: Airplane Health Management*, The Boeing Company.

31. Goranson, U.F. and Rogers, J.T. "Elements of damage tolerance verification. in 12th Symposium of International Commercial Aeronautical Fatigue" 1983. Toulouse, France.

32. McIver, K., "Aging Aircraft and Durability System Level Concepts for Airframe Airworthiness Management," The Boeing Company, Final Report Task Order Agreement No. NNL10AB23T, (2011).

33. Chaparro, A. and Groff, L.S. "Human Factors Survey of Aviation Technical Manuals Phase 1: Manual Development Procedures ," DOT/FAA/AR-01/43 (2001), U.S. Department of Transportation Federal Aviation Administration.

34. Harris, C.E. "FAA/NASA International Symposium on Advnaced Structural Integrity Methods for Airfrmae Durability and Damage Tolerance" in *Proceedings of a symposium jointly sponsored by the Federal Aviation Administration, Washington, DC, and the National Aeronautics and Space Administration, Washington, D. C.* May 4-6 1994. Hampton, VA.

35. Bruce, D.A., Buynak, C.F., and Lindgren, E. "Non-Destructive Evaluation (NDE) and Aircraft Availability" in *RTO AVT-144 Workshop* October 3-5 2006. Vilnius, Lithuania.

36. "Aircraft Accident Report: United Airlines Flight 232 Mc Donnell Douglas DC-10-10 Sioux City, Iowa," NTSB/AAR-90106, (July 19 1989), National Transportation Safety Board.

37. Sheperd, D.P., Ward, T.J., Wisbey, A., Vermeulen, B., and Boyd Lee, A.D. "Life Extension Methods in Aero Engines" OMMI, 2004. **3**(1): p. 1-15.

38. Amer, K.B. "A New Philosophy of Structural Reliability, Fail Safe Versus Safe Life: The 1988 Alexander A. Nikolsky Lecture," Journal of the American Helicopter Society, 1989. **34**(1): p. 3-13.

39. "Department of Defense Handbook: Engine Structural Integrity Program (ENSIP)," MIL-HDBK-1783B w/change 2, (2004), Department of Defense.

40. *General Electric's Bondtracer*. Available from: http://www.ge-mcs.com/en/ultrasound/thickness-gauges/bondtracer.html.

41. *Defense, Space & Security*. Available from: http://www.boeing.com/defense-space/support/maintenance/commercial/maus.html.

42. Mrad, N. "SHM implementation" in *Fly by Wireless Workshop (FBW), 2011 4th Annual Caneus*. June 14-17 2011. Montreal, Canada.

43. Mofakhami, M.R. and Pinsonnault, J. "A Prospective for Structural Health Monitoring System Implementation on Civil Aircraft" in *International Workshop Smart Materials, Structures & NDT in Aerospace*. November 2-4, 2011. Montreal, Quebec, Canada.

44. Foote, P., Gordon, G., and Derriso, M., "The Aerospace Industry Steering Committee on Structural Health Monitoring and Management (AISC-SHM): Progress on SHM guidelines for aerospace," 2011: International Workshop on Structural Health Monitoring, Stanford University.

45. Majcher, K., *10 Technologies To Watch* in Overhaul & Maintenance p. 24, January 01 2011.

46. *Enhanced Airworthiness Program for Airplane Systems/Fuel Tank Safety (EAPAS/FTS). Federal Register, 2007. 72(216): p. 63364-63414.*

47. Federal Aviation Administration, *Commercial Off-the-Shelf Wiring System Diagnostics Evaluations*, Final Report, January 2007, DOT/FAA/AR-06/61.

48. Eclypse International. Available from: http://www.eclypse.org/

49. Astronics Corp.; Available from: http://astronics.com.

50. 3M Aerospace and Aircraft Maintenance. Available from: http://solutions.3m.com/wps/portal/3M/en_US/Aerospace/Aircraft.

51. Song, E., Shin, Y.- J. ; Stone, P.E., Wang, J., Choe, T.-S., Jong-Gwan Yook, J.-G., Park, J. B. "Detection and location of multiple wiring faults via time-frequency domain reflectometry," *IEEE Trans. Electromagn. Compat.*, vol. 51, no. 1, pp. 131-138, Feb. 2009.

52. Sadok, M, Huang, N., Walz, M. "Hilbert-Huang Transform for Wire Diagnostics in Aircraft," 9th Joint FAA/DoD/NASA Aging Aircraft Conference, March 2006.

53. Smith, P., Furse, C., and Gunther, J. "Analysis of spread spectrum time domain reflectometry for wire fault location," *IEEE Sensors J.* vol. 5, no. 6, pp. 1469-1478, Dec. 2005.

54. The Boeing Company and Brookhaven National Laboratory, *Evaluation of Broadband Impedance Spectroscopy for Prognostic/Diagnostic Technique for Electric Cables Used in Nuclear Power Plants*, June 2006. NUREG/CR-6904

55. Federal Aviation Administration, *Demonstration and Validation of the Excited Dielectric Test Method to Detect and Locate Defects in Aircraft Wiring Systems*, Final Report, January 2005. DOT/FAA/AR-04/43.

56. NASA TechBriefs, "Material for Lifecycle Optimization," August 2011.

57. Schneider, L., Howard, K., Glover, S., Lockner, T., and Dinallo, M. "A new capability to detect and locate insulation defects in complex wiring systems," Electrical Insulation Magazine, IEEE, 2005. 21(4): p. 14-20.

58. *Livewire Innovation: Wire Integrity Tester (WIT)*. Available from: http://livewireinnovation.com/products-and-services/wit/.

59. Killdeer Mountain Manufacturing, http://www.kmmnet.com/.

60. *Lectro Mech*. Available from: www.lectromech.com.
61. Sinnett, M. "787 No-Bleed Systems: Saving Fuel and Enhancing Operational Efficiencies," Aero Quartely, 2008.
62. Johnson, R.L. "Safety by Design: A Gulfstream Perspective," 2008: Aircraft Builders Council Conference.
63. Spitzer, C.R., "Honeywell Primus Epic Aircraft Diagnostic Maintenace System," in *Digital Avionics Handbook: Elements, Software and Functions. Avionics*. 2007, CRC Press. p. 19.
64. Celaya, J.R., Kulkarni, C., Biswas, G., Saha, S., and Goebel, K. "A Model-based Prognostics Methodology for Electrolytic Capacitors Based on Electrical Overstress Accelerated Aging" in *Annual Conference of the Prognostics and Health Management Society*. September 25-29 2011. Montreal QC, Canada.
65. Balaban, E., Saxena, A., Narasimhan, S., Roychoudhury, I., Goebel, K.F., and Koopmans, M.T. "Airborne Electro-Mechanical Actuator Test Stand for Development of Prognostic Health Management Systems" in *Annual Conference of the Prognostics and Health Management Society*. October 10-16 2010. Portland, Oregon
66. Byington, C., Watson, M., Edwards, D., Stoelting, P. "A Model-Based Approach to Prognostics and Health Management for Flight Control Actuators," IEEE Aerospace Conference Proceedings, 2004.
67. Cox, D.C. and Perez-Kite, R. "Battery state of health monitoring, combining conductance technology with other measurement parameters for real-time battery performance analysis" in *INTELEC 22nd International Telecommunications Energy Conference*. 2000. Phoenix, AZ.
68. Goebel, K., Saha, B., Saxena, A., Celaya, J., and Christophersen, J. "Prognostics in Battery Health Management," Instrumentation & Measurement Magazine, IEEE, 2008. **11**(4): p. 33-40.
69. Volponi, A. and Wood, B. "Aircraft Propulsion Health Management," in *System Health Management*. 2011, John Wiley & Sons, Ltd. p. 389-403.
70. Jaw, L.C. and Mattingly, J.D. "Aircraft Engine Controls: Design, System Analysis, and Health Monitoring," 2009: American Institute of Aeronautics and Astronautics.
71. Sieverding, C.H. and Mathioudakis, K., eds. *Gas Turbine Condition Monitoring and Fault Diagnosis*. 2003, Von Karman Institute for Fluid Dynamics, Lecture Series 2003-01.
72. Doel, D.L. "TEMPER---A Gas-Path Analysis Tool for Commercial Jet Engines," Journal of Engineering for Gas Turbines and Power, 1994. **116**(1): p. 82-89.
73. *AIR 1872A - Guide To Life Usage Monitoring And Parts Management For Aircraft Gas Turbine Engines*, 1998, SAE International.
74. Tauber, T. "AIR 1828 - A Guide to Gas Turbine Engine Oil System Monitoring," SAE Technical Papers, 1983.
75. Cassidy, K. "Qualifying an On-Line Diagnostic and Prognostic Sensor for Fixed and Rotary Wing Bearings and Gears," presented at the IEEE Aerospace Conference, Big Sky, Montana, March 2008.
76. http://www.pw.utc.com/media_center/press_releases/2009/05_may/5-27-2009_781268.asp
77. Zakrajsek, J.J. "An Investigation of Gear Mesh Failure Prediction Techniques," NASA-TM-102340, (November 1 1989), NASA Glenn Research Center.
78. Vehicle Integrated Prognostic Reasoner, NASA NRA NNL09AD44T,
79. Mylaraswamy, D. "Vehicle Integrated Prognostic Reasoner VIPR," presented at the NASA Aviation Safety Program Annual Technical Meeting, May 10–12, 2011, St. Louis, MO.

80. Derriso, Mark M., "Integrated Systems Health Management – The Key to Future Aerospace System," presented at Intelligent Systems Health Management Technical Interchange Meeting, Houston TX, February 2005.

81. Harvey, S., Ingham, M., and Rozier, K.Y. "Intelligent systems" in Aerospace America p. 41, December 2010.

82. *A web-based collaboration tool for those interested in data mining and systems health.* Available from: https://c3.nasa.gov/dashlink/.

83. Feary, M.S. "A Toolset for Supporting Iterative Human Automation: Interaction in Design," 20100012861, (March 2010), NASA Ames Research Center; NASA Langley Research Center.

84. Hunter, G. "Development and Testing of Propulsion Health Management," presented at the NASA Aviation Safety Program Annual Technical Meeting, May 10–12, 2011, St. Louis, MO.

85. Donald, W. S. "Control Considerations using a Generic ARM Seeker," Decision and Control including the 15th Symposium on Adaptive Processes, 1976 IEEE Conference on, Dec. 1976; 1976; pp. 1164–1165.

86. Jung, D. and Tsiotras, P. "Modelling and Hardware-in-the-loop Simulation for a Small Aerial Vehicle" in *AIAA Infotech at Aerospace*. May 2007. Rohnert Park, CA.

87. Manaï, M., Desbiens, A., and Gagnon, E. "Identification of a UAV and Design of a Hardware-in-the-Loop System for Nonlinear Control Purposes" in *AIAA Guidance, Navigation, and Control Conference and Exhibit, AIAA Atmospheric Flight Mechanics Conference and Exhibit*. August 18 2005. San Francisco, CA.

88. McManus, I.A., Greer, D.G., and Walker, R.A. "UAV Avionics ``Hardware in the Loop'' Simulator" in *10th Australian International Aerospace Congress*. July 29 - August 1 2003. Brisbane, Queensland, Australia.

89. Sitz, J.R. and Vernon, T.H. "Flight control system design factors for applying automated testing techniques," in *Digital Avionics Systems Conference, 1990. Proceedings., IEEE/AIAA/NASA 9th*. October 15-18 1990. Virginia Beach, VA.

90. Bauer, J.E., Clarke, R., and Burken, J.J. "Flight Test of the X-29A at High Angle of Attack: Flight Dynamics and Controls," 1995, NASA Dryden Flight Research Center.

91. Sitz, J.R., *F-18 Systems Research Aircraft Facility*, 1992, NASA. p. 1-32.

92. Rausch, V.L., McClinton, C.R., Sitz, J., and Reukauf, P. "NASA's Hyper-X Program" in *51st International Astronautical Congress*. October 2-6 2000. Rio de Janeiro, Brazil.

93. Shy, K.S., Hageman, J.J., and Le, J.H. "The Role of Aircraft Simulation in Improving Flight Safety Through Control Training" in *AIAA Modeling and Simulation Technologies Conference and Exhibit*. August 5-8 2002. Monterey, CA.

94. Tuegel, E.J., Ingraffea, A.R., Eason, T.G., and Spottswood, S.M. "Reengineering Aircraft Structural Life Prediction Using a Digital Twin". International Journal of Aerospace Engineering, 2011. **2011**: p. 1-14.

95. Tuegel, E.J. "Airframe Digital Twin: An Overview" in *Aircraft, Airworthiness & Sustainment Conference*. April 2-5 2012. Baltimore, MD.

96. Thomas, M.A. "Framework for Cohesive Zone Model Based Multiscale Damage Evolution in a Fatigue Environment," 2011, Wright State University.

97 Hess, A., Calvello, G., and Dabney, T. "PHM a key enabler for the JSF autonomic logistics support concept" in Proceedings of the 2004 IEEE Aerospace Conference, Big Sky, Montana, USA, 6–13 March 2004, vol. 6, pp. 3543–3550.

98  Hess, A. and Fila, L. "The joint strike fighter PHM concept: potential impact on aging aircraft problems" in Proceedings of the 2002 IEEE Aerospace Conference, Big Sky, Montana, USA, 9–16March 2002, vol. 6, pp. 3021–3026.

99.  Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., and Wa, L., *Modeling, Simulation, Information, Technology & Processing Roadmap - Technology Area 11*, 2010, NASA.

100. Piascik, B., Vickers, J., Lowry, D., Scotti, S., Stewart, J., and Calomino, A., *Materials, Structures, Mechanical Systems, and Manufacturing Roadmap - Technology Area 12*, 2010, NASA.

101. Yarema, S.Y. "On the contribution of G. R. Irwin to fracture mechanics," Materials Science, 1996. **31**(5): p. 617-623.

102. Mettu, S.R., Shivakumar, V., Beek, J.M., Yeh, F., Williams, L.C., Forman, R.G., McMahon, J.J., and Newman, J.C., Jr., *NASGRO 3.0: A Software for Analyzing Aging Aircraft* 1999, Johnson Space Center; Langley Research Center.

103. Newman, J.C., Jr. and Harris, C.E. "Fracture Mechanics Research at NASA Related to the Aging Commercial Transport Fleet" in *International Conference on Aging Aircraft and Structural Airworthiness*. November 19-21 1991. Washington, DC: NASA.

104. Harris, C.E., James H. Starnes, J., and Shuart, M.J. "Advanced Durability and Damage Tolerance Design and Analysis Methods for Composite Structures," NASA/TM—2003-212420, (June 2003), NASA Langley Research Center.

105. Prosser, W.H., Wu, M.C., Allison, S.G., DeHaven, S.L., and Ghoshal, A., "Structural Health Monitoring Sensor Development" at NASA Langley Research Center. in *International Conference on Computational & Experimental Engineering and Sciences (ICCES '03)*. July 25-29 2003. Corfu, Greece.

106. Richards, L., Parker, A.R., Ko, W.L., and Piazza, A. "Real-time In-Flight Strain and Deflection Monitoring with Fiber Optic Sensors" in *Space Sensors and Measurements Techniques Workshop*. August 5 2008. Nashville, TN.

107. Madaras, E.I., Prosser, W.H., Studor, G., Gorman, M.R., and Ziola, S.M. "Structural Health Monitoring of the Space Shuttle's Wing Leading Edge," AIP Conference Proceedings, 2006. **820**: p. 1756-1763.

108. Smith, S.W., Newman, J.A., Piascik, R.S., and Glaessgen, E.H. "An Active Crack Healing Mechanism for Metallic Materials," LAR–17681–1.

109. Wallace, T.A., Smith, S.W., Piascik, R.S., Horne, M.R., Messick, P.L., Alexa, J.A., Glaessgen, E.H., and Hailer, B.T. "Strain-Detecting Composite Materials," 20100190026, (July 29 2010), USA as represented by the Administrator of the National Aeronautics and Space Administration.

110. Gordon, K.L., Siochi, E.J., Grimsley, B.W., Cano, R.J., and Czabaj, M.W. "Puncture-healing Thermoplastic Resin Carbon Fiber Reinforced Composites towards More Damage/Impact Tolerant Systems," LAR–18131–1.

111. White, S.R., Sottos, N.R., Geubelle, P.H., Moore, J.S., Kessler, M.R., Sriram, S.R., Brown, E.N., and Viswanathan, S. "Autonomic healing of polymer composites," Nature, 2001. **409** (6822): p. 794-797.

112. Smits, J. K., Kite, M. T., Moore, T. C., Wincheski, R. A., Ingram, J. L., Watkins, A. N., Williams, P. A., Carbon nanotube-based sensor and method for detection of crack growth in a structure, U. S. Patent 7,278,324,B2, 2007.

113. Wilson, W. C., Perey, D. F., Atkinson, G. M., Barclay, R. O. "Passive Wireless SAW Sensors for IVHM," Frequency Control Symposium, IEEE International, May 19-21; 2008; p. 273-277.

114. *Decadal Survey of Civil Aeronautics: Foundation for the Future*. 2006: The National Academies Press pg. 31.

115. Molent, L., and Aktepe, B. "Review of Fatigue Monitoring of Agile Military Aircraft," Fatigue & Fracture of Engineering Materials & Structures 2000**, 23** (9), p. 767-785.

116. Tikka, J.; Hedman, R.; Silijander, A., *Strain Gauge Capabilities in Crack Detection*, Fourth International Workshop on Structural Health Monitoring, Stanford, CA, Stanford, CA, 2003; p. 812–819.

117. Shanmugham, S.; Liaw, P. K. "Detection and Monitoring of Fatigue Cracks" in *ASM Handbook, Fatigue and Fracture*, ASM International: 1996; **19**, pp 210-223.

118. Gouldstone, C.; Brogan, J.; Greenlaw, R.; Gambino, R. J.; Gutleber, J.; Sanjay, S.; Longtin, J. "Embedded Resistive Strain Sensors for Harsh Environments," Aerospace Conference, IEEE, Big Sky, MT, March 4–11; Big Sky, MT, 2006; 10 pp.

119. Banaszak, D.; Brown, D. L.; Laird, D. J. "Antonomous Environmental Definition of C-130 Flap Well Skin Panel," *Journal of the IEST* 2005**, 48** (1), p. 50-61.

120. Arms, S. W.; Townsend, C. P.; Galbreath, J. H.; Newhard, A. T., "Wireless Strain Sensing Networks," 2nd European Workshop On Structural Health Monitoring, Munich, Germany, July 7-9; Munich, Germany, 2004; p 7-9.

121. Duncan, R.G., Childers, B.A., Gifford, D.K., Pettit, D.E., Hickson, A.W., and Brown, T.L. "Distributed Bragg grating sensing technique for test article damage detection and monitoring," SPIE Conference Proceedings, 2003. **5050**: p. 367-375.

122. Froggatt, M.E. "Apparatus and method for measuring strain in bragg gratings," U.S. Pat. 5798521, (August 25 1998), The United States of America as represented by the Administrator of the National Aeronautics and Space Administration.

123. Johnson, K. "Ultrasonic Consolidation of Titanium Alloys for High Performance Military Aircraft Damage Repair," 2006 Commercial Technologies for Maintenance Activities (CTMA) Symposium Williamsburg, VA, March 29, 2006.

124. Allison, S.G., Winfree, W.P., and Wu, M.C. "Fiber Optic Bragg Grating Sensors for Thermographic Detection of Subsurface Anomalies" in *Aging Aircraft Conference*. May 4-7 2009. Kansas City, MO.

125. Brook A., C., Mark E., F., Sidney G., A., Thomas C. Moore, S., David A., H., Christopher F., B., and Dawn C., J. "Use of 3000 Bragg Grating Strain Sensors Distributed on Four Eight-Meter Optical Fibers During Static Load Tests of a Composite Structure," SPIE Conference Proceedings, 2001. **4332**: p. 132-142.

126. Moore, J.P., Childers, B.A., Froggatt, M.E., Cook, A.L., Coffey, N.C., Coen, L.J., Diamond, J.K., Huynh, P.T., Riley, E.M., Stover, S.K., Vipavetz, K.G., Wells, J.E., Woodman, K.L., Armstrong, C.D., Sirkis, J.S., and Peng, Y.T. "An Overview of the Fiber Optic Sensing System for Hydrogen Leak Detection in the Space Shuttle Discovery on STS - 96," 1999. Optical Society of America.

127. Wu, M.-C. and DeHaven, S.L. "High-sensitivity cryogenic temperature sensors using pressurized fiber Bragg gratings," SPIE Conference Proceedings, 2006. **6189**: p. 169-175.

128. Schuet, S., Timucin, D., and Wheeler, K. "A Model-Based Probabilistic Inversion Framework for Characterizing Wire Fault Detection Using TDR," IEEE Transactions onInstrumentation and Measurement, 2011. **60** (5): p. 1654-1663.

129. Schuet, S.R., Timucin, D.A., and Wheeler, K.R. "Shielded-twisted-pair cable model for chafe fault detection via time-domain reflectometry," (2012), NASA Ames Research Center.

130. *The Advanced Diagnostics and Prognostics Testbeds (ADAPT)* Available from: http://ti.arc.nasa.gov/tech/dash/diagnostics-and-prognostics/adapt-diagnostics/.

131. Balaban, E., Saxena, A., Bansal, P., Goebel, K.F., and Curran, S. "Modeling, Detection, and Disambiguation of Sensor Faults for Aerospace Applications," Sensors Journal, IEEE, 2009. **9** (12): p. 1907-1917.

132. Zakrajsek, J.J., Oswald, F.B., Townsend, D.P., and Coy, J.J. "Gear noise, vibration, and diagnostic studies at NASA Lewis Research Center" in *1st International Conference on Gear Box Noise and Vibration*. April 10-11 1990. Cambridge, England.

133. Zakrajsek, J.J., Townsend, D.P., Lewicki, D.G., Decker, H.J., and Handschuh, R.F. "Transmission diagnostic research at NASA Lewis Research Center" in *2nd International Conference on Gearbox Noise, Vibration, and Diagnostics*. November 16-17 1995. London, UK.

134. Dempsey, P.J. "Integrating Oil Debris and Vibration Measurements for Intelligent Machine Health Monitoring ," TM-2003-211307, (March 2003), NASA Center for Aerospace Information.

135. Zaretsky, E.V. and Anderson, W.J. "Relation Between Rolling-Contact Fatigue Life and Mechanical Properties for Several Aircraft Bearing Steels," Trans. ASTM, 1960. **60**: p. 627-649.

136. Manson, S.S., Halford, G.R., and Spera, D.A. "The role of creep in high temperature low cycle fatigue, in Advances in creep design," Smith, A.I. and Nicolson, A.M., Editors. 1971, Halsted Press Division. p. 229-249.

137. "Aircraft engine diagnostics," in NASA conference publication 2190 (May 6-7 1981), NASA Scientific Technical Information Branch: Lewis Research Center.

138. Sallee, G.P. "Performance deterioration based on existing (historical) data; JT9D jet engine diagnostics program," (1978), NASA Center for Aerospace Information.

139. Wulf, R.H. and Center, L.R. "Engine Diagnostics Program: CF6-50 Engine Performance Deterioration," 1980: NASA-Lewis Research Center.

140. Volponi, A. and Simon, D.L. "Enhanced Self Tuning On-Board Real-Time Model (eSTORM) for Aircraft Engine Performance Health Tracking," NASA/CR-2008-215272, (2008), NASA Glenn Research Center.

141. Huron, E., Bain, K., Mourer, D., and Gabb, T. "Development of High Temperature Capability P/M Disk Superalloys," Green, K.A., Caron, P., Gabb, T.P., Fahrmann, M.G., Huron, E.S., Woodard, S.R., and Reed R.C., Editors. *Proceedings of the Eleventh Internation Symposium on Superalloys*. TMS, 2008. p.181-190.

142. Xie, M., Mitchell, S.C., LaChapelle, D.G., Braley, M.S., Roberts, G.D., and Hopkins, D. "Composite Containment Case for Turbine Engines," United States of America Patent 7,390,161. June 24, 2008.

143. Braley, M. S., Dorer, J. D., and Roberts, G. D. "Composite Case Armor for Jet Engine Fan Case Containment," United States of America Patent 8,016,543. September 13, 2011.

144. Roberts, G.D., Pereira, J.M., Braley, M.S., Arnold, W.A., Dorer, J.D., and Watson, W.R., "Design and Testing of Braided Fan Case Materials and Composites," NASA TM-2009-215811, 2009.

145. NTSB. NTSB Identification: ENG06IA018, National Trasportation Safety Board, 2008.

146. Sudbrack, C.K., Draper, S.L., Gorman, T.T., Telesman, J., Gabb, T.P., and Hull, D.R. "Oxidation and the Effects of High Temperature Exposures on Notched Fatigue Life of an Advanced Powder Metallurgy Disk Superalloy," Proceedings of the 12th International Symposium of Superalloys, TMS, 2012.

147. Telesman, J., Gabb, T.P., Yamada, Y., Ghosn, L.J., Hombach, D., Jayaraman N. "Dwell Notch Low Cycle Fatigue Behavior of a Powder Metallurgy Nickel Disk Alloy," Proceedings of the 12th International Symposium of Superalloys. TMS, 2012.

148. Gabb, T.P., Telesman, J., Kantzos, P.T., and Garg, A. "Effects of Temperature on Failure Modes for a Nickel-Base Superalloy," J. of Failure Analysis and Prevention 7, no. 1 (2007), p.56-65.

149. Gabb, T.P., Garg, A., Miller, D.R., Sudbrack, C.K., Hull, D.R., Johnson, D., Rogers, R.B., Gayda, J., and Semiatin, S.L., "Formation of Minor Phases in a Nickel-based Disk Superalloys," NASA TM-2012-217604, 2012.

150. Kohlman, L.W., Revilock, D.M., Ruggeri, C.R., Pereira, J.M. and Roberts, G.D. "Update on the Progress of Hygrothermal Aging of Triaxial Braided Carbon/Epoxy Composites," The 2012 Aircraft Airworthiness and Sustainment Conference, Baltimore, MD, 2012.

151. Kohlman, L.W., Bail, J. L., Roberts, G.D., Salem, J. A., Martin, R. E. "A notched coupon approach for tensile testing of braided composites," *Composites: Part A*, 2012, doi:10.1016/j.compositesa.2011.12.013.

152. Miller, S.G., Roberts, G.D., Bail, J.L., Kohlman, L.W., and Binienda, W.K. "Effects of Hygrothermal Cycling on the Chemical, Thermal, and Mechanical Properties of 862/W Epoxy Resin," High Performance Polymers, June 2012.

153. Simon, D.L. and Garg, S. "Optimal Tuner Selection for Kalman Filter-Based Aircraft Engine Performance Estimation," Journal of Engineering for Gas Turbines and Power, 2010. **132**(3): p. 031601- 031610.

154. Simon, D.L. "An integrated architecture for on-board aircraft engine performance trend monitoring and gas path fault diagnostics" in *Jannaf Propulsion Meeting*. 2010. Cleveland, Ohio: National Aeronautics and Space Administration, Glenn Research Center.

155. Frederick, Dean K., DeCastro, Jonathan A., and Litt, Jonathan S. "User's Guide for the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS)," NASA TM-2007-215026, October 2007.

156. Csank, J., May, R. D., Litt, J.S., and Guo, T, "Control Design for a Generic Commercial Aircraft Engine," AIAA–2010–6629, 46th AIAA Joint Propulsion Conference & Exhibit, Nashville, TN, July 25-28, 2010, NASA/TM—2010-216811, October 2010.

157. Simon, D.L., Garg, S., Hunter, G.W., Guo, T.-H., and Semega, K.J. "Sensor Needs for Control and Health Management of Intelligent Aircraft Engines," NASA TM—2004-213202, (2004), NASA Glenn Research Center.

158. Hunter, G.W. "Morphing, Self-Repairing Engines: A Vision for the Intelligent Engine of the Future," in *AIAA/ICAS International Air & Space Symposium, 100th Anniversary of Flight* 2003: Dayton, OH.

159. Hunter, G.W., Oberle, L.G., Baaklini, G.Y., Perotti, J.M., and Hong, T., "Intelligent Sensors for Health Management," in *System Health Management*. 2011, John Wiley & Sons, Ltd. p. 405-418.

160. For example, the Propulsion Instrumentation Working Group is a consortium of engine companies that cooperatively address critical turbine engine-development test

instrumentation and sensor issues (http://www.piwg.org). A list sensor needs have been drafted, many of which are areas of active NASA research.

161. Lekki, J., Bencic, T., Gyekenyesi, A., Adamovsky, G., Hunter, G.W., Tokars, R., and Woike, M. "Aircraft Engine Sensors for Integrated Vehicle Health Management" in *57th Joint Propulsion Meeting*. May 3-7 2010. Colorado Springs, CO.

162. Hunter, G., Neudeck, P.G., Beheim, G., Okojie, R.S., Chen, L., Spry, D.J., and Trunek, A., "An Overview of Wide Bandgap SiC Sensor and Electronics Development at NASA Glenn Research Center," ECS Transactions, 2007. **11**(5): p. 247-257.

163. Flanagan, P.M. and Lekki, J. "A self-diagnostic system for the M6 accelerometer," in *37th Joint Propulsion Conference and Exhibit*. July 8-11 2001. Salt Lake City, Utah: National Aeronautics and Space Administration, Glenn Research Center.

164. Kurtoglu, T., Leone, K., Revely, M., and Sandifer, C. "A Study on Current and Emerging Technologies and Future Research Requirements for Integrated Vehicle Health Management," (September 2008).

165. Ivey, P.C. and Grant, R.K. "The New Potential for Joint UK/US Studies in Sensor Technology for HCF Studies in Gas Turbine Aero- Engines" in *22nd AIAA Aerodynamic Measurement Technology and Ground Testing Conference*. June 24-26 2002. St. Louis, MO.

166. Lindeman, R., and Stange W. "ISA Standards for Turbine Engine Test Cell Instrumentation" Presented at the ISA 58th International Instrumentation Symposium, June 4-7 2012. San Diego, CA..

167. Hunter, G.W., Xu, J.C., and Makel, D.B. "Case Studies in Chemical Sensor Development," *BioNanoFluidic MEMS*, Hesketh, P.J., Editor. 2008, Springer US. p. 197-231.

168. Hunter, G.W., Xu, J.C., Liu, C.-C., and Makel, D.B. "Microfabricated Chemical Sensors for Aerospace Applications," in *The Mems Handbook, Second Edition*, Gad-el-Hak, M., Editor. 2005, CRC Press.

169. "Multi-Species Gas Sensor Array Project," N66604–07–C–1828, in Test and Evaluation/Science and Technology Program, Navair Naval Undersea Warfare Center.

170. Ward, B.J., Wilcher, K., and Hunter, G.W. "Gas Microsensor Array Development Targeting Enhanced Engine Emissions Testing" in *AIAA Infotech @ Aerospace*. April 20-22 2010. Atlanta, GA.

171. Thompson, H.A. "Wireless and Internet communications technologies for monitoring and control," Control Engineering Practice, 2004. **12**(6): p. 781-791

172. Hunter, G.W., Xu, J.C., Neudeck, P.G., Makel, D.B., Ward, B.J., and Liu, C.-C. "Intelligent Chemical Sensor Systems for In-Space Safety Applications," in *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*. July 09-12 2006. Sacramento, CA.

173. Neudeck, P.G. and Gardner, B.G. "Silicon Carbide Electronics," 2010; Available from: http://www.grc.nasa.gov/WWW/SiC/discoveries.html.

174. Okojie, R.S. "Stable 600 °C silicon carbide MEMS pressure transducers," in *Sensors and Systems for Space Applications*, Howard, R.T. and Richards, R.D., Editors. 2007, Proceedings of the SPIE.

175. Philip, N. "SiC Technology," in *The VLSI Handbook*, Chen, W.-K., Editor. 1999, CRC Press.

176. Neudeck, P.G., Okojie, R.S., and Liang-Yu, C., "High-temperature electronics - a role for wide bandgap semiconductors?," Proceedings of the IEEE, 2002. **90**(6): p. 1065-1076.

177. Neudeck, P.G., Spry, D.J., Liang-Yu, C., Beheim, G.M., Okojie, R.S., Chang, C.W., Meredith, R.D., Ferrier, T.L., Evans, L.J., Krasowski, M.J., and Prokop, N.F. "Stable Electrical Operation of 6H-SiC JFETs and ICs for Thousands of Hours at 500 °C," Electron Device Letters, IEEE, 2008. **29**(5): p. 456-459.

178. Spry, D.J., Neudeck, P.G., Chen, L.-Y., Beheim, G.M., Okojie, R.S., Chang, C.W., Meredith, R.D., Ferrier, T.L., and Evans, L.J., "Fabrication and Testing of 6H-SiC JFETs for Prolonged 500 °C Operation in Air Ambient," Materials Science Forums, 2009. **600-603**: p. 1079-1082.

179. Schwartz, Z.D. and Ponchak, G.E. "High temperature performance of a SiC MESFET based oscillator," in *IEEE MTT-S International Microwave Symposium Digest*. June 12-17 2005. Long Beach, CA.

180. Ponchak, G.E., Scardelletti, M.C., Taylor, B., Beard, S., Meredith, R.D., Beheim, G.M., Hunter, G.W., and Kiefer, W.S. "High temperature, wireless seismometer sensor for Venus" in *IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*. January 15-18 2012. Santa Clara, CA.

181. Hunter, G.W., Beheim, G.M., Ponchak, G.E., Scardelletti, M.C., Meredith, R.D., Neudeck, P.G., Jordan, J.L., Chen, L.Y., Xu, J.C., Biaggi-Labiosaa, A.M., Ward, B.J., and Makel, D.B. "Development of High Temperature Smart Sensor Systems" in *219th Meeting of the Electrochemical Society*. May 1-6 2011. Montreal, Canada: ECS.

182. Roundy, S.J., "Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion," 2003, The University of California, Berkeley.

183. Roundy, S., Steingart, D., Frechette, L., Wright, P.K., and Rabaey, J.M. "Power Sources for Wireless Sensor Networks" in *Wireless Sensor Networks, First European Workshop, EWSN*. January 19-21 2004. Berlin, Germany.

184. Martin, L.C. "Advances in thin film thermocouple durability under high temperature and pressure testing conditions," ed. Fralick, G.C. and Taylor, K.F. 1999, Cleveland, Ohio: NASA Lewis Research Center.

185. Fralick, G., Wrbanek, J., and Blaha, C. "Thin Film Heat Flux Sensor of Improved Design," in *48th International Instrumentation Symposium*. May 5-9 2002. San Diego, CA.

186. Dynys, F. and Sayir, A. "Self-Powered Wireless Sensors," in *Materials Science & Technology Conference & Exhibition*. October 5-9 2008. Pittsburgh, PA.

187. Sayir, A., Dynys, F., Sehirlioglu, A., and Caillat, T. "Thermoelectric Properties of CrSi2-Si(Ge) Eutectic for Oxidizing Environment," in *Materials Science & Technology Conference & Exhibition*. September 16-19 2007.

188. Hunter, G.W., Beheim, G.M., Ponchak, G.E., Scardelletti, M.C., Meredith, R.D., Dynys, F.W., Neudeck, P.G., Jordan, J.L., and Chen, L.Y. "Development of High Temperature Wireless Sensor Technology Based on Silicon Carbide Electronics," ECS Transactions, Vol. 33, No. 8, pp. 269–281, 2010.

189. *Decadal Survey of Civil Aeronautics: Foundation for the Future*. 2006: The National Academies Press.

190. "National Aeronautics Research and Development Plan," (February 2010), National Science and Technology Council.

191. "Goal 2: Safer Systems Objective 2B - Provide safety enhancements for airborne systems," in National Aviation Safety Strategic Plan v1.0B (June 10 2011), Joint Planning and Development Office.

192. Keller, K., Swearingen, K., Sheahan, J., Bailey, M., Dunsdon, J., Przytula, K.W., and Jordan, B. "Aircraft electrical power systems prognostics and health management," in *IEEE Aerospace Conference*. 2006.

193. Ramsey, J.W., "Engine Indications: Advanced sensors, faster processing and smaller sizes improve monitoring and control of aircraft engines, enhancing operations," in Avionics Today, November 1 2008..

194. Sallee, G.P., Gibbons, D.M. "AIA / AECMA Project Report on Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR)," November, 1998.

195. Guo, T.-H. and Litt, J.S. "Resilient Propulsion Control Research for the NASA Integrated Resilient Aircraft Control (IRAC) Project" in *Infotech @ Aerospace Conference and Exhibit*. May 7-10 2007. Rohnert Park, CA.

196. Guo, T.-H. and Litt, J.S. "Risk Management for Intelligent Fast Engine Response Control" in *AIAA Infotech @ Aerospace Conference and AIAA Unmanned*. April 2009. Seattle, WA.

197. Csank, J.T., Chin, J.C., May, R.D., Litt, J.S., and Guo, T.-H. "Implementation of Enhanced Propulsion Control Modes for Emergency Flight Operation" in *Infotech@Aerospace 2011 Conference*. March 29-31 2011. Saint Louis, MO.

198. Evans, D., *Wiring Matters: An overview of the Aircraft Wiring Issue* in Aviation Maintaince p. 30-34, August 2006.

199. Burcham, F.W., Jr., Fullerton, C.G., and Maine, T.A. "Manual Manipulation of Engine Throttles for Emergency Flight Control," NASA/TM—2004-212045, January 2004.

200. Litt, J.S., Frederick, D.K., and Guo, T.-H. "The Case for Intelligent Propulsion Control for Fast Engine Response," AIAA–2009–1876, AIAA Infotech@Aerospace Conference, Seattle WA, June 6–9, 2009.

| 1. REPORT DATE *(DD-MM-YYYY)*<br>01-03-2013 | 2. REPORT TYPE<br>Technical Memorandum | | 3. DATES COVERED *(From - To)* |
| --- | --- | --- | --- |
| 4. TITLE AND SUBTITLE<br>A Concept of Operations For An Integrated Vehicle Health Assurance System | | | 5a. CONTRACT NUMBER |
| | | | 5b. GRANT NUMBER |
| | | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S)<br>Hunter, Gary, W.; Ross, Richard, W.; Berger, David, E.; Lekki, John, D.; Mah, Robert, W.; Perey, Daniel, F.; Schuet, Stefan, R.; Simon, Donald, L.; Smith, Stephen, W. | | | 5d. PROJECT NUMBER |
| | | | 5e. TASK NUMBER |
| | | | 5f. WORK UNIT NUMBER<br>WBS 284848.02.03.03.02.01 |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>National Aeronautics and Space Administration<br>John H. Glenn Research Center at Lewis Field<br>Cleveland, Ohio 44135-3191 | | | 8. PERFORMING ORGANIZATION REPORT NUMBER<br>E-18575 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>National Aeronautics and Space Administration<br>Washington, DC 20546-0001 | | | 10. SPONSORING/MONITOR'S ACRONYM(S)<br>NASA |
| | | | 11. SPONSORING/MONITORING REPORT NUMBER<br>NASA/TM-2013-217825 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>Unclassified-Unlimited<br>Subject Category: 03<br>Available electronically at http://www.sti.nasa.gov<br>This publication is available from the NASA Center for AeroSpace Information, 443-757-5802 | | | |
| 13. SUPPLEMENTARY NOTES | | | |

**14. ABSTRACT**
This document describes a Concept of Operations (ConOps) for an Integrated Vehicle Health Assurance System (IVHAS). This ConOps is associated with the Maintain Vehicle Safety (MVS) between Major Inspections Technical Challenge in the Vehicle Systems Safety Technologies (VSST) Project within NASA's Aviation Safety Program. In particular, this document seeks to describe an integrated system concept for vehicle health assurance that integrates ground-based inspection and repair information with in-flight measurement data for airframe, propulsion, and avionics subsystems. The MVS Technical Challenge intends to maintain vehicle safety between major inspections by developing and demonstrating new integrated health management and failure prevention technologies to assure the integrity of vehicle systems between major inspection intervals and maintain vehicle state awareness during flight. The approach provided by this ConOps is intended to help optimize technology selection and development, as well as allow the initial integration and demonstration of these subsystem technologies over the 5 year span of the VSST program, and serve as a guideline for developing IVHAS technologies under the Aviation Safety Program within the next 5 to 15 years. A long-term vision of IVHAS is provided to describe a basic roadmap for more intelligent and autonomous vehicle systems.

| 15. SUBJECT TERMS<br>Health management; Health assurance; Vehicle safety; Airframe; Propulsion; Avionics; Sensors; Algorithms; Composites; Wiring; Intelligent systems | | | | | |
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| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON<br>STI Help Desk (email:help@sti.nasa.gov) |
| a. REPORT<br>U | b. ABSTRACT<br>U | c. THIS PAGE<br>U | UU | 132 | 19b. TELEPHONE NUMBER *(include area code)*<br>443-757-5802 |