National Aeronautics and Space Administration
Aeronautics Research Mission Directorate
Aviation Safety Program

Integrated Vehicle Health Management

"Automated detection, diagnosis, prognosis to enable mitigation of adverse events during flight."

Technical Plan, Version 2.01

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This document was developed over the past several months by NASA to define the rationale, scope and detailed content of a comprehensive Aviation Safety, Integrated Vehicle Health Management research project. It contains references to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The document also references potential opportunities for cooperation with external organizations in areas that are currently considered to be of common interest or benefit to NASA. This document should be considered a reference document and not a detailed research implementation plan.

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IVHM Technical Plan

1. Project Scope

The goal of the Integrated Vehicle Health Management (IVHM) project is to develop validated tools, technologies, and techniques for automated detection, diagnosis and prognosis that enable mitigation of adverse events during flight. Adverse events include those that arise from system, subsystem, or component faults or failures due to damage, degradation, or environmental hazards that occur during flight. The project offers a research program that addresses both the *hardware* and the *software* aspects of the aircraft. Because software health management is a field in its infancy, this project will perform the foundational research needed to develop technologies for automated detection, diagnosis, prognostics, and mitigation of adverse events due to aircraft *software*. Much effort from past programs has been placed on understanding safety issues that arise from hardware issues. However, as the nation moves towards the vision of NextGen, software, and the issues that are associated with it, will have growing impact on aircraft health. Software health management capabilities are much broader and require much more sophistication than what is covered by standard software verification and validation technologies.

The new IVHM capabilities will enable the rapid detection and diagnosis of these adverse events (in both the hardware and the software) essential to the safe operation of the vehicle and will enable the estimation of the condition severity and the remaining useful life (RUL) with confidence bounds for the affected system(s). Maintenance workers, crew, adaptive configuration systems and other control systems can take advantage of the estimated remaining useful life to enhance the safety profile of the aircraft. Although this project is primarily focused on the vehicle, it also addresses some adverse events at the system-level of the national air transportation system. Developing the real-time automated reasoning and decision making tools and techniques to integrate messages from the health management systems of individual aircraft and combining them with results from analysis of fleet-wide vehicle health assessments is a critical challenge for the IVHM project. Therefore, the project will develop probabilistic models of potential fault and failure modes and data mining algorithms to analyze large heterogeneous data sources from current aircraft fleets to develop static and dynamic models of potential system failures. This capability will enable aircraft-wide and system-wide research and will be used to continue development of tools and technologies in support of the Aviation Safety and Information Analysis and Sharing (ASIAS) collaboration with the Federal Aviation Administration (FAA). Through foundational research in data mining, the project will create technologies that identify precursors to failures through analysis of system-wide data sets.

The IVHM project will coordinate its research and development activities (in-house, NRAs, SBIRs) with the other projects in the Aviation Safety Program, other programs and projects within ARMD, and other non-ARMD programs and projects, and will collaborate with academia, industry, and other government agencies to leverage their expertise and technological advances in this field. These coordination activities are discussed in Section 2.

2. Relevance

Fatal accidents in the worldwide commercial jet fleet from 1987-2005 were due primarily to i) controlled flight into terrain, ii) loss-of-control in flight, and iii) system/component failure or malfunction (non-powerplant, powerplant) (ref. 1). In a coordinated effort to improve aviation safety, industry and government worked together to reduce the number of fatal commercial aircraft accidents, which dropped by 65% during the period of 1996-2007 (ref. 2). However, with the projected increase in departure rates, it is estimated that the accident rates will increase significantly (ref 2). Accidents due to controlled flight into terrain have been virtually eliminated through the addition of various safeguards, but the same cannot be said for accidents due to loss-of-control in flight and system/component failure or malfunction. Better technologies, tools, and methods are needed to safeguard against these causes of accidents which are anticipated to escalate in NextGen, N+1, N+2, etc. System/component failures and malfunctions are recognized as contributing factors to aircraft loss-of-control in flight, so safeguarding against them will reduce the number of fatal accidents in the two top accident categories. The IVHM project directly addresses these needs through the development of innovative technologies, tools, and methods to protect against *hardware* system/component failure or malfunction as well as against the growing concerns of *software-related* failure or malfunction.

Safety risks due to hardware and software-related failures and malfunctions will increase with the complexity that comes with more sophisticated capabilities and the greater reliance on automation. Thus, it is necessary to develop new capabilities that will provide accurate on-board detection, diagnosis, prognosis, and mitigation of adverse conditions during flight. These new capabilities will manage the health of both hardware and software systems and should be developed in an incremental fashion and tested in a wide range of aircraft.

The goals of the IVHM project are aligned with the Aviation Safety Program Goals (ref. 3), the Agency Roles and Responsibilities for NASA (ref. 4), the 2006 Decadal Survey of Civil Aeronautics (ref. 5), the 2007 National Plan for Aeronautics Research and Development and Related Infrastructure (ref. 6), and the 2007 Next Generation Air Transportation System Research and Development Plan (ref. 7) as stated below:

Aviation Safety Program Goals defined in the NASA FY08 Budget Request (ref. 3) include the following: Develop technologies, tools, and methods to i) improve aircraft safety for current and future aircraft, ii) overcome safety technology barriers that would otherwise constrain the realization of the Next Generation Air Transportation System, iii) support space exploration activities, such as enabling self-reliant and intelligent systems necessary for long-duration travel requirements of future space vehicles.

NASA’s Roles and Responsibilities defined in Section V of the National Aeronautics Policy (ref. 4) include the following: “*The National Aeronautics and Space Administration (NASA) should maintain a broad foundational research effort aimed at preserving the intellectual stewardship and mastery of aeronautics core competencies so that the nation’s world-class aeronautics expertise is retained. These core competencies also include key aeronautical capabilities that support NASA’s human and robotic space activities.*”

The 2006 Decadal Survey of Civil Aeronautics conducted a comprehensive review of the current aeronautics technologies and has put forth 51 high priority R&T challenge areas (ref. 5). The following IVHM technology development areas are among the highest rated challenges:

- Integrated vehicle health management (C1)
- Methodologies, tools, and simulation and modeling capabilities to design and evaluate complex interactive systems (E1)
- Fault-tolerant and integrated vehicle health management systems (D5)
- Use of operational and maintenance data to assess leading indicators of safety (E8b)
- Multifunctional materials (C10)
- Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits (B3)

Each of these challenges is a development area within this IVHM Technical Plan and has associated task descriptions, key milestones, metrics, and metrics rationale.

The 2007 National Plan for Aeronautics Research and Development and Related Infrastructure (ref. 6) established the high priority national aeronautics research and development challenges, goals and objectives, and provided guidance for their development. The following IVHM technology development areas are among the Aviation Safety R&D Goals and Objectives:

- Develop technologies to reduce accidents and incidents by developing vehicle health management systems to determine the state of degradation for aircraft subsystems; developing and demonstrating tools and techniques to mitigate in-flight damage, degradation, and failures; developing reconfigurable health management systems for managing suspect regions in N+2 vehicles. (Goal 1)
- Develop advanced tools that translate numeric (continuous and discrete) system performance data into usable, meaningful information for prognostic identification of safety risks for system operators and designers by: developing advanced methods to automatically analyze textual safety reports and extract system performance information for prognostic identification of safety risks for system operators and designers and developing fundamentally new data mining algorithms to support automated data analysis tools to integrate information from a diverse array of data resources (numeric and textual) to enable rapid prognostic identification of system-wide safety risks. (Goal 2)

Each of these goals is a development area within this IVHM Technical Plan and has associated task descriptions, key milestones, metrics, and metrics rationale.

The NextGen Research and Development Plan FY2009-2013 (ref. 7) detailed requirements for needed technologies, the technology gaps in aviation safety, and the agencies responsible for each area. The priorities are on research in procedures, technologies, and automated recovery capabilities to address the most significant safety issues, including loss of control, weather encounters, and mechanical failures. The IVHM project addresses the following priorities:

- Complete applied research on system health management to support alternative NextGen equipage decisions (R-1280)
- Complete applied research on vulnerability discovery to support an alternative selection decision for the NextGen Aviation Safety Analysis and Information Sharing (ASAIS) capability (R-0020)
- Complete applied research on advanced properties for continued airworthiness of aircraft to support alternative NextGen equipage decisions (R-1270)

Each of these areas is a development area within this IVHM Technical Plan and has associated task descriptions, key milestones, metrics, and metrics rationale.

Health Management Challenges

One of the most important challenges facing aviation safety today is safeguarding against system/component failures and malfunctions. This is because hardware faults and failures are very difficult to detect, diagnose, and mitigate in-flight with existing technologies. Consequently, when these problems occur they can lead to catastrophic accidents. Data from the FAA and NTSB are clear: subsystem, component failures and hazards together contribute 24% to onboard fatalities, and are underlying factors in many of the 26% of the accidents caused by loss-of-control in flight. NTSB accident data covering 7,571 US-registered aircraft from 1980 to 2001, broken down by the accident causes (hardware malfunctions only), show that 52% of the hardware-induced accidents were aircraft system related, 36% were caused by propulsion system components, and the remaining 10% were caused by failures in the airframe. Landing gear caused 36 accidents, turbine/turboprop engines contributed to 33, and flight controls contributed to 10 accidents. Similarly, incident data again shows that turbine engines and landing gear were the largest contributors to hardware-induced incidents, each causing 19% of incidents, and flight controls causing 9%. FAA data covering 40,964 incidents involving US airplanes from 1998 through 2003 shows that for commercial air carriers, commuters, and on-demand air taxis, about 67% of the incidents were caused by a combination of system and component failure and malfunction, fire/smoke, and power loss. Other problems noted in the CAST report include (ref. 8 and 9): i) lack of realistic simulation of propulsion system malfunctions and aircraft response; ii) lack of adequate trend information; iii) inadequate or lack of sensors/equipment to indicate damage from Foreign Object Damage (FOD), Bill of Material Object Damage (BMOD), or ground equipment collision; iv) improper assessment of failure modes and effects analyses; v) failure to provide warning of flight critical system unsafe status; and vi) ice protection system design inadequate for conditions encountered. Each of these problematic areas is addressed by the IVHM project in preparation for NextGen, N+1, N+2, etc.

Equally serious threats are those associated with computer software-related risks. These risks are a growing concern especially for NextGen and beyond because of the increased complexity of aircraft and the higher reliance on automation. Listed below are instances of accidents caused by computer software-related flaws and deficiencies: (ref. 10):

- Crash due to worldwide bug in barometric altimetry in Ground Proximity Warning System
- Crash due to computer failure to warn crew of unset flaps and incorrect thruster indicator
- Crash due to digital engine control failure
- Break-off of two engines caused by autopilot malfunction
- Airplane break-up mid-air when thruster reverser deployed in mid-air; software flaw in proximity switch electronic unit suspected
- Accident blamed on experimental software
- Accident due to random memory initialization in flight management computers
- Crash due to wrong computer readout for navigation

These incidents show how computer software-related errors can be a serious threat to aircraft safety that when left unresolved can lead to catastrophic accidents. The IVHM project plans to make fundamental investments in new technology to support the development of software health management capabilities.

Thus the critical issues that face aviation safety with respect to the goals of IVHM for NextGen and beyond reside in both the hardware and software domains. The IVHM project addresses adverse conditions caused by both domains, with emphasis on maturing technologies for hardware systems and foundational research for software systems.

2.1. Current State of the Art

The current state of IVHM development is focused on putting a variety of sensor systems onboard an aircraft along with intelligent software to automatically interpret the various sensor output streams. These data provide inputs to prognostic systems that then assess issues such as structural integrity and remaining component/subsystem life. Two state-of-the-art hardware health management systems are Honeywell's Aircraft Diagnostic and Maintenance System (ADMS) and the Joint Strike Fighter (JSF) Prognostics Health Management (PHM) System.

The ADMS (ref. 11) is a fault propagation modeling system that is used in the Boeing 777. The ADMS is an avionics system that has been designed to be scalable and extensible to various aircraft, and as such represents the next generation in modular avionics systems. The ADMS is an evolution of several maintenance features used in previous systems, and is comprised of the Central Maintenance Computer (CMC), Aircraft Conditioning Monitoring Function (ACMF), and the built-in-test (BIT) functionality of the various systems on the aircraft. ADMS provides coverage of more than 200 aircraft subsystems, and serves as the maintenance access point to all subsystems through a user-friendly graphical interface. The ADMS literally provides nose-totail coverage on most aircraft. ADMS performs root cause diagnostics to eliminate cascading faults and provide correlation between system faults and flight deck effects. ADMS is configurable through a separately loadable diagnostics database. It provides fault information to the ground through an aircraft data link, provides onboard loading of navigation files, databases, and system software, and generates reports to the cockpit printer.

The current state of the art in aircraft IVHM is exemplified by the Joint Strike Fighter (JSF) program. This program has incorporated prognostics health management (PHM) into its design using sensors, advanced processing and reasoning, and a fully integrated system of information and supplies management. The on-board JSF PHM system is hierarchical, dividing the aircraft into areas such as propulsion and mission systems. Area data are generated by a mixture of dedicated, purpose-built sensors and analysis on existing control sensors to identify degradation and failures, which are compiled and correlated by area reasoners and then correlated by system-level model-based reasoners. Maintenance datalinks transmit vehicle health data to ground-based information systems focused on maintenance and management of the supply chain. Prognostic events are detected by prognostic built-in-tests, automated post-flight trending, and reasoning with an emphasis on disambiguating sources of degradation rather than failure. An autonomic logistics information system provides logistic support to the end-user and also provides off-board trending across the entire JSF fleet. Although these represent significant achievements, it is widely acknowledged that more work is required to build reliable, effective health management systems that build upon fundamental breakthroughs in detection, diagnostics, and prognostics to enable safe and efficient implementation of mitigation strategies. For example, in a presentation given by an official in the JSF Program Office (ref. 9), several key areas were highlighted that needed improvement and attention. These include the development of tools and technologies to:

- understand the physics of failure,
- improve state awareness,
- understand the dynamics of incipient crack growth,
- understand fault and failure progression rates,
- understand material properties under different loading conditions,
- develop better data fusion methods, and
- understand the effects of failures across the vehicle.

The current state of software health management is focused on standalone application software modules that operate independently. At present, software health management typically resides with the Real-Time Operating System (RTOS) and interfaces to a recovery strategy table defined by the aircraft design or system integrator. Each application software module is usually developed and verified to the level of criticality appropriate to its function, and is responsible for redundancy management for its specific function and for signal selection and failure monitoring of inputs from external systems or other systems. The application software modules, which may be developed by independent sources, are built to be completely isolated from other modules so that one cannot cause adverse effects in another when integrated into an aircraft-level platform. Communication between the application software modules and the RTOS ensures that there is no violation of the partition interfaces and that no application monopolizes a resource or leaves another suspended. The RTOS manages communications and receives interrupts associated with failure and error, relaying these incidents to the software health monitor function, which in turn directs the necessary actions to enable recovery or otherwise. Throughout, current software health management systems employ pre-defined recovery tables to handle known software flaws and vulnerabilities. Currently, IVHM software health management technology is in the infancy stage. For NextGen aircraft, advancement in software health management capabilities will be needed to accurately interpret sensor data to support autonomous decision making for handling software integrity failures, whether previously anticipated or not, at the vehicle-level.

The IVHM Project will advance the state of the art in both hardware and software health management through the research approach described in this document.

2.2. Benefits of the Research

The development of validated multidisciplinary integrated vehicle health management tools, technologies, and techniques to enable detection, diagnosis, prognosis, and mitigation in the presence of adverse conditions during flight will provide effective solutions to deal with safety related challenges facing NextGen aircraft. As more advanced hardware systems and more intelligent automation software become integrated into NextGen aircraft, the need for effective IVHM capabilities will grow accordingly.

Generally, the research benefits will include:

- Improved understanding, characterization, and prediction of coupled effects associated with failure that threaten aircraft flight safety;
- Robustness and fault tolerance to component/subsystem/aircraft/system-level off-nominal performance, anomalous behavior, faults, and damage;
- Improved/optimal performance of aircraft systems at the vehicle-wide level;
- Potential to reduce cost associated with aircraft maintenance and flight down time; and
- Safety assurance of advanced safety critical technologies for the National Airspace System (NAS), NextGen, N+1, N+2, etc

For NextGen operations, the benefits of effective IVHM capabilities will accelerate the transformation of the air transportation system to accept i) 2-3x increases in air traffic, ii) increased reliance on automation, iii) increased diversity of vehicles, and iv) increased complexity in the system.

2.3. Cross Project, Program, and Agency Collaborations

The IVHM project will coordinate its research and development activities (in-house, NRAs, SBIRs) with the other projects in the Aviation Safety Program and other programs and projects within ARMD, and will collaborate with academia, industry, and other government agencies to leverage their expertise and technological advances in aviation safety. The coordination and collaboration efforts will include the following:

- Integrated Intelligent Flight Deck (IIFD) Project – Collaboration with IIFD will facilitate the development, acceptance, and use of IVHM data-mining technologies, tools, and methods for aviation safety system analysis and assessment. The two projects will coordinate efforts on the development and application of automated text analysis and anomaly detection tools, flight data analysis, the development of flight data emulators, and icing detection and diagnosis.
- Aircraft Aging and Durability (AAD) Project – Collaboration with AAD will facilitate the development of IVHM and AAD technologies, tools and methods for the detection, diagnosis, prognosis, and mitigation of degradation and damage in wiring and airframe structure in flight. The projects will work cooperatively on self healing materials, crack propagation (metallic fatigue), composite delamination, and the development of testbeds.
- Integrated Resilient Aircraft Control (IRAC) Project – Collaboration with IRAC will facilitate and accelerate the development of IVHM technologies to detect, diagnose, and prognosticate hardware and software issues associated with avionics. IVHM will focus on the detection, diagnosis and prognosis of avionics faults and malfunctions, actuator failure and damage, and avionics transient effects resulting from operation in a harsh environment (neutron particles, electromagnetic fields, lightning). Both projects will work on the integration of IVHM and IRAC technologies, the development of a systems architecture, the development of shared testbeds, and the conduct of joint ground-based and flight experiments.
- Fundamental Aeronautics (FA) – Communication with FA will enable the IVHM project to better understand the trends and requirements of future aircraft. This will include interaction with the Multi-Disciplinary Analysis and Optimization Inter-Disciplinary Groups (MDAO IDG) regarding NexGen, N+1, N+2, N+3 aircraft requirements and infusion of IVHM technology. This interaction will accelerate the acceptance of IVHM technologies, tools, and methods for future aircraft.
- Airspace Systems Program (ASP) – Collaboration with ASP on an IVHM NRA study on health monitoring of airspace will provide the IVHM project with a better understanding of airspace safety issues, and will stimulate broader development and application of IVHM technologies.
- Exploration Systems Mission Directorate (ESMD) –The ESMD needs better tools and methods to ensure safe launch, flight, and mission operation of the many components of the overall Constellation and Exploration architecture. The IVHM project is developing new technologies that can provide better monitoring and diagnosis capabilities while minimizing sensor mass and volume requirements. Both parties will benefit from the successful development, acceptance, and use of IVHM tools and methods.
- Joint Army Navy NASA Air Force (JANNAF) – IVHM and JANNAF will work together on the development of a business case for IVHM for solid and liquid rocket propulsion. This effort encourages communication and cooperation with other DOD agencies. It will help to further establish IVHM as a viable capability for critical applications.
- Air Force Research Laboratory (AFRL) –The IVHM project will work collaboratively with AFRL on IVHM architectures, secured data integration and access, and modeling and simulation tools. This effort will enable the IVHM project to pursue research in a more cost-effective manner by making use of or optimizing AFRL’s work and advancements in IVHM technologies.

In short, these collaborations and coordination activities will accelerate IVHM research and development efforts, reduce overall development cost, and lead to a more integrated and effective operational concept for NextGen aircraft.

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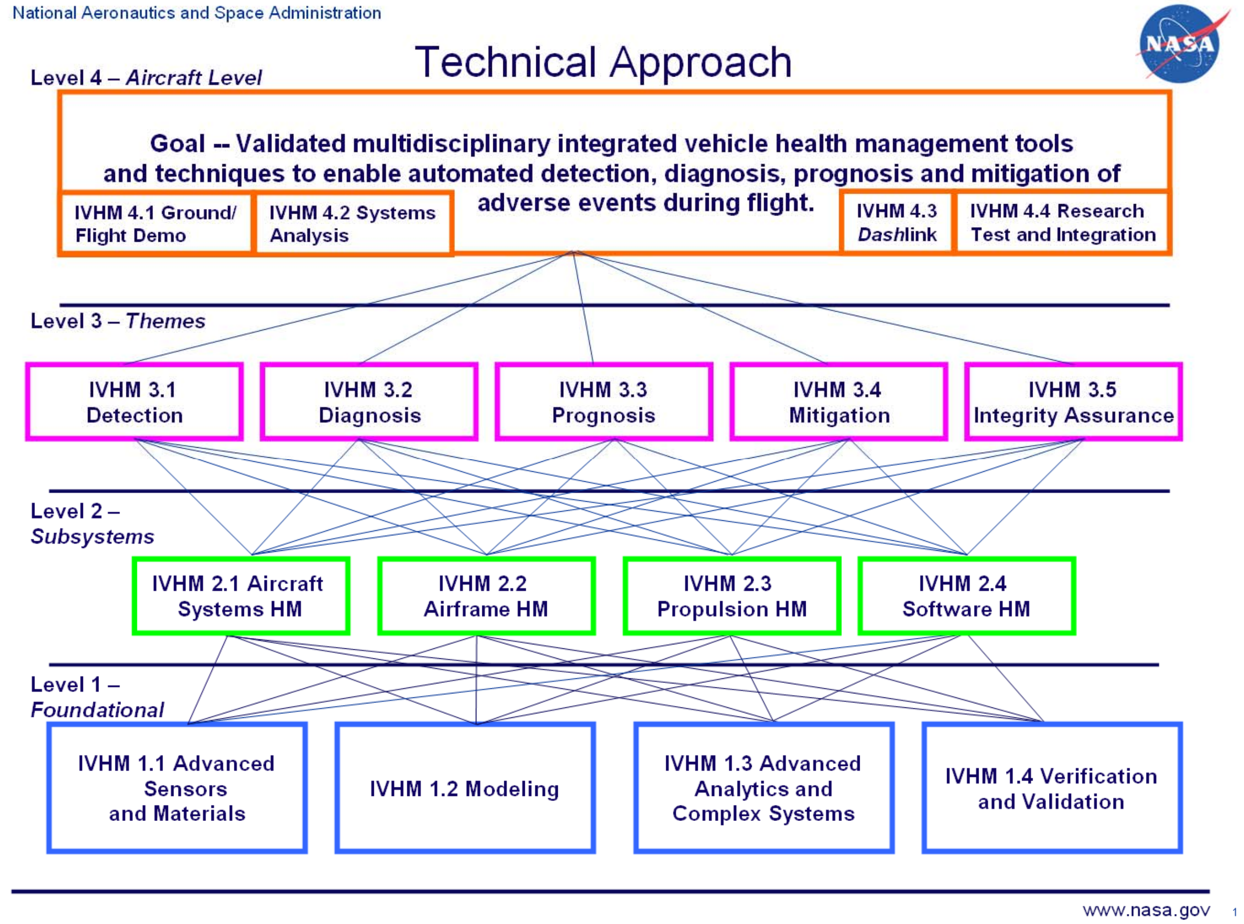
3. Milestones and Metrics

The five-year IVHM roadmap with detailed milestones and metrics addresses the NASA and US aerospace industry goals and needs. The roadmap addresses the key challenges associated with aviation safety, contains aggressive but realistic goals for aircraft currently on the drawing board, and strategically positions NASA to address longer-term needs associated with future generation vehicles. The overall technical approach and associated master schedule are shown in Figures 1(a) and (b) and Figure 2. The Figure 2 milestones represent a balanced strategy with the Level 4 goal of developing validated multidisciplinary integrated vehicle health management technologies, tools and techniques to enable automated detection, diagnosis, prognosis that enable mitigation of adverse events during flight. The foundational research to support the IVHM project is conducted at Level 1 as depicted in Figure 1(b), covering Advanced Sensors and Materials, Modeling, Advanced Analytics and Complex Systems, and Verification and

Validation. The goal of the Level 3 themes is to develop an integrated toolset to enable the detection, diagnosis, and prognosis of adverse events during flight, whereas Level 2 provides the validated technologies across the major subsystems (Aircraft, Airframe, Propulsion and Software) of an aircraft to enable the Level 3 goal. The Associate Principal Investigators (APIs) for IVHM reside at Level 3 and provide the necessary oversight of technologies at the aircraft level to enable IVHM capabilities across the aircraft. Detailed descriptions of the milestones and metrics are listed at the end of each technical section. In addition to milestones, the IVHM project features WAYPOINTS. WAYPOINTS represent the culmination of periods of progress that are not measured with a metric; rather, an outcome is defined and used to gauge progress associated with a WAYPOINT. WAYPOINTS are specifically labeled as such in the milestone tables. Selected key project deliverables over the next five year period, including the key program commitments, are listed in Table 1.

As described above, the milestones and metrics in IVHM are constructed to represent a logical flow from foundational research to the overall goal of the IVHM project. Thus, each milestone has an associated metric and a rationale for the metric. Each metric is defined based on an assessment of the state of the art (SoA) today. As the project evolves, we anticipate that these metrics will change to accommodate the new knowledge generated within the project and in the outside research community. To maintain programmatic awareness of the future trends in the aviation industry and the potential implications for Aviation Safety and IVHM, the IVHM project has a Systems Analysis task at Level 4 which surveys the SoA both within and outside the project. As new discoveries arise, the Systems Analysis task will disseminate the information and the associated implications for IVHM through the relevant areas in the project, thus providing regular updates.

Because of the multidisciplinary nature of IVHM, an essential component of the project is the dissemination of results, simulation and real-world data sets, algorithms, and other relevant documentation to the public. To enable this dissemination, the IVHM project has a Level 4 task to develop and maintain a Discovery in Aeronautics Systems Health website known as DASHlink.



National Aeronautics and Space Administration

Technical Approach

Level 4 – *Aircraft Level*

Goal -- Validated multidisciplinary integrated vehicle health management tools and techniques to enable automated detection, diagnosis, prognosis and mitigation of adverse events during flight.

IVHM 4.1 Ground/ Flight Demo

IVHM 4.2 Systems Analysis

IVHM 4.3 *Dash*link

IVHM 4.4 Research Test and Integration

Level 3 – *Themes*

IVHM 3.1 Detection

IVHM 3.2 Diagnosis

IVHM 3.3 Prognosis

IVHM 3.4 Mitigation

IVHM 3.5 Integrity Assurance

Level 2 – *Subsystems*

IVHM 2.1 Aircraft Systems HM

IVHM 2.2 Airframe HM

IVHM 2.3 Propulsion HM

IVHM 2.4 Software HM

Level 1 – *Foundational*

IVHM 1.1 Advanced Sensors and Materials

IVHM 1.2 Modeling

IVHM 1.3 Advanced Analytics and Complex Systems

IVHM 1.4 Verification and Validation

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Figure 1(a). This figure shows the levels of research within IVHM and the logical flow from foundational research to project-level goals. The Associate Principal Investigators (APIs) reside at Level 3; Task Leads reside at Levels 2 and 1.

IVHM 1.1 Advanced Sensors and Materials

- Active & Embedded Sensing
- Sensing in Icing & Other Extreme Environments
- Self-healing materials

IVHM 1.2 Modeling

- Damage Characterization and Propagation
- Estimating Remaining Useful Life
- Bayesian Modeling Techniques
- Design Tools
- System Level Modeling

IVHM 1.3 Advanced Analytics and Complex Systems

- Data Mining
- Decision Science
- Adaptive Reconfiguration
- System-Level Analysis

IVHM 1.4 Verification and Validation

- Detection of Critical Faults in Complex Systems
- Observability
- V&V in Nonlinear, Non-Gaussian Systems

Figure 1(b). IVHM Level I detail

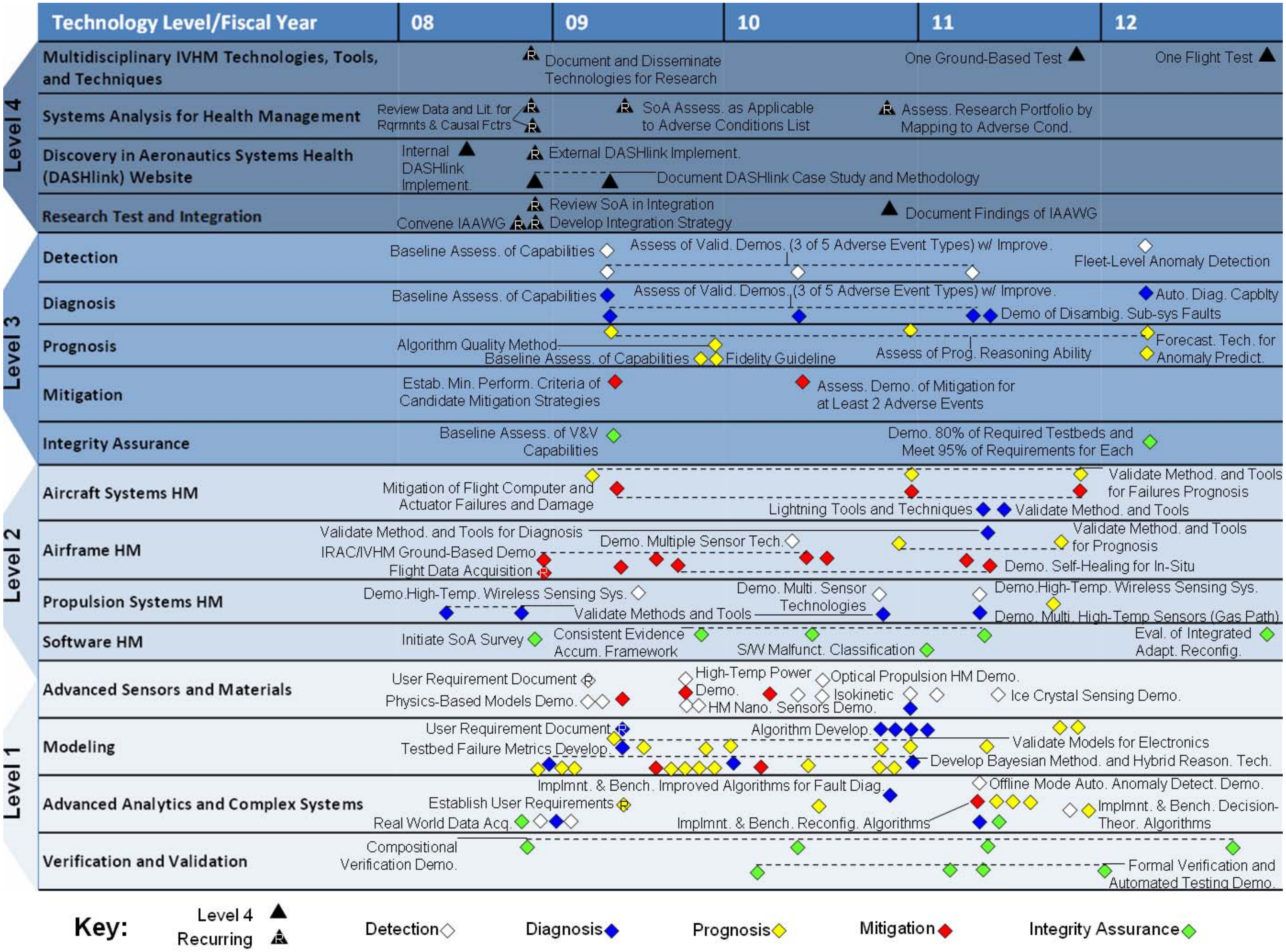

Figure 2. Major milestones over the next five years in the IVHM Project.

Project Deliverables to Support PART and IBPD milestones (Next 5 Years)	**Date**
Using aircraft landing gear system as a testbed, develop and validate Integrated Vehicle Health Management sensor fusion, fault detection, and isolation methods. (IVHM v2.01 1.2.2.2 i)	2008
Demonstrate a 10% improvement in estimation accuracy of integrated gas path sensing and diagnostics for aircraft engine health. (IVHM v2.01 2.3.2.1 iii)	2009
Using 2008 as a baseline, demonstrate, on a representative current generation electro-mechanical system testbed, improved IVHM via Bayesian methods and/or models for varying operating conditions and demonstrate fault detection/diagnosis on at least three faults types such as discrete, continuous, abrupt, transient, or cascading faults. Examine tradeoff between accuracy and diagnosis time. Demonstrate, in experiments, better than 95% accuracy for diagnosing faults. (IVHM v2.01 1.2.2.2 iii)	2010
Demonstrate integrated self-healing material system concepts for in-situ mitigation of damage in structural elements subjected to representative loading. (IVHM v2.01 2.2.4.1)	2011
Forecasting technology that has the ability to predict at least 3 known anomalies in real or emulated data of large, fleet-wide heterogeneous data sources. (IVHM v2.01 3.3.4)	2012

Table 1. This table shows the selected project milestones that support the Integrated Budget Program Commitment and PART milestones over the next five years.

4. Technical Approach

The goal of the IVHM Project is to arrive at a set of validated multidisciplinary integrated vehicle health management tools, technologies, and techniques to enable automated detection, diagnosis, and prognosis, that enable system-level mitigation of adverse events during flight.

All milestones and tasks within IVHM are related to this goal. The cornerstone of this approach is the Level Diagram shown in Figure 1(a) that illustrates a logical flow of foundational research in Level 1 towards subsystems in Level 2. Level 3 represents an integration of the subsystems in Level 2 into key intellectual themes and Level 4 represents the integration of research to achieve the project.

The *system level research* in Level 4 focuses on the evaluation of multidisciplinary integrated methods, tools, and technologies for achieving the IVHM goal; Systems Analysis to maintain project-wide situational awareness of internal and external trends regarding IVHM related issues; the DASHlink website, which is the critical link between NASA and researchers in academia, industry, and other government labs; and Research Test and Integration to develop a plan for testing and integration of vehicle health management technologies and establish a working group to study systems integration and architecture issues.

The *multidisciplinary research themes* at Level 3 focus on methods and tools required for the detection, diagnosis, and prognosis that enable mitigation of adverse events during flight from the perspective of the total vehicle. Each of these four elements corresponds to a key multidisciplinary research activity. The Associate Principal Investigators (APIs) reside at Level 3. In addition, a fifth theme, Integrity Assurance, is at Level 3 and focuses on the development of advanced tools and techniques to enable verification and validation of complex systems and the requisite testbeds for technology demonstrations.

The subsystem research at Level 2 focuses on methods and tools that are required for the development of integrated health management systems within each of the four major elements of the aircraft: Airframe, Propulsion, Aircraft Systems, and Software Systems. The key tasks of this level include the application of simulation methods, experimental methods, and related verification and validation techniques for physics-based models to develop tools and techniques that are related to specific aspects of the aircraft subsystem.

The development of Software Health Management technologies, tools, and techniques represents an important area of innovation in the IVHM project. While software verification and validation (V&V) is a critical component to aviation safety, errors can occur even after verification and validation have been completed on a piece of software because of the large number of interactions that software has with other pieces of software. Also, changes in hardware without the appropriate changes in software can lead to faults. Thus, the IVHM project will invest in V&V tools and technologies for software systems and also in the development of methods for the detection, diagnosis, prognosis, and mitigation of adverse events caused by software errors assuming that the software has already gone through a standard V&V process. Our software approach will parallel that used with hardware components. For example, turbine engines are highly reliable devices due to manufacturing techniques and decades of research. However, even though extensive measures are applied to these systems to ensure reliability, we still research the fundamental areas of detection, diagnosis, prognosis, and mitigation because of unknown, unexpected interactions between the system and other systems, unmodeled flaws, and other similar contingencies.

The *foundational research* at Level 1 focuses on four key elements: Advanced Sensors and Materials, Modeling, Advanced Analytics and Complex Systems, and Verification and Validation. The Advanced Sensors and Materials element focuses on the foundational research to develop adaptive sensing techniques, sensors that will operate in extreme environments, embedded sensor technologies and self-healing materials. The Modeling element in Level 1 is a key enabler of the overall project goals of diagnosis and prognosis. The modeling element develops probabilistic techniques to characterize and understand damage propagation and to form estimates of remaining useful life. The Advanced Analytics and Complex Systems element in Level 1 is concerned with the development of advanced data mining algorithms to enable large-scale analysis of complex, heterogeneous signals from single aircraft as well as data from aircraft fleets or the airspace system. Finally, the Verification and Validation element in Level 1 is concerned with the development of tools and techniques to predict or detect critical faults in highly complex and integrated systems that employ advanced technologies such as sensors, artificial intelligence, data fusion, diagnostics, prognostics and mitigation. The use of these technologies for detecting critical faults in propulsion, flight, and airframe systems is without precedent in civil aviation, and will require a high level of confidence that the diagnosis and predictions made by onboard health management systems are correct and reliable.

Level 4 – Aircraft-Level Research

The following are statements of the problems and the associated approaches to their solutions for the three elements of the Aircraft-level Research at Level 4. Element IVHM 4.1 addresses evaluation of multidisciplinary IVHM technologies, tools, and techniques, Element IVHM 4.2 addresses systems analysis for health management, Element IVHM 4.3 addresses the development of the Discovery in Aeronautics Systems Health (DASHlink) website, and Element IVHM 4.4 addresses Research Test and Integration. The project-level milestones are described for each of these three elements.

IVHM 4.1 Evaluation of Multidisciplinary IVHM Technologies, Tools, and Techniques

Problem Statement: The focus of the IVHM project is to develop technologies, tools, and techniques to enable the automated detection, diagnosis, and prognosis, that enable system-level mitigation of adverse events during flight. The technologies generated by this project will be revolutionary and highly multidisciplinary due to the nature of the problems they address. The capabilities that will be developed are intended to support the diverse future needs of aircraft operators, aircraft manufacturers, designers of NextGen, academia, the space exploration community, and other entities with an interest in system health management. The challenges associated with a project of this scope rely on developing robust methods to address each element of the stated goal that can be validated in realistic environments. While the replication of realistic environments may require flight testing, other techniques including advanced ground-based testbeds and software simulations will also be used to validate the technologies developed in this project. Such validation is necessary for the adoption of these technologies into next generation aircraft. The adoption of IVHM tools and technologies in the future aircraft depends on bringing them into the early stages of the design process; thus, the IVHM project will participate in the Multidisciplinary Design, Analysis, and Optimization Interdisciplinary Group (MDAO IDG) in the NASA Fundamental Aeronautics program to ensure the infusion of appropriate tools, technologies, and results into the design process.

Previous Related Research: There have been several IVHM related research projects conducted within NASA, with notable contributions coming from the X-37 IVHM Experiment, the Deep Space 1 mission, the Exploration Technology Development Program Integrated Systems Health Management (ETDP-ISHM) project and the Aviation System Monitoring and Modeling (ASMM) project. Outside of NASA, the Joint Strike Fighter program serves as a key indicator of the state-of-the-art in vehicle health management and is often heralded as one of the first major projects to include IVHM technologies as part of the initial design process. A forerunner of the IVHM concept was “on-condition maintenance.” The DoD has championed this concept for years and has demonstrated the cost savings compared with the scheduled maintenance that most commercial operators use. IVHM carries the concept of on-condition maintenance to the next level by reducing costs but also enhancing the safety profile of the vehicle. Although a key motivation for on-condition maintenance is to develop tools and technologies to enable maintenance only when warranted, the safety profile of the aircraft is also improved because it allows errors caused by the implementation of maintenance procedures to be avoided.

While each of these projects had the overall goal of developing and advancing IVHM technologies for their associated platform, a few highlights about the background of these projects are in order. The goals of the X-37 program were to: “demonstrate benefits of in-flight IVHM to the operation of a Reusable Launch Vehicle, to advance the Technology Readiness Level of this IVHM technology within a flight environment, and to operate IVHM software on the Vehicle Management Computer. The scope of the experiment was to perform real-time fault detection and isolation for X-37's electrical power system and electro-mechanical actuators.” The project developed a software system that enabled the automatic discovery and diagnosis of failures. The Deep Space 1 mission was the first flight test of this software system, known as Livingstone, and was the first space mission that used IVHM technology.

The focus of the ETDP-ISHM project was to develop tools and techniques for automated fault detection and isolation on rocket systems and subsystems including the solid and liquid propulsion systems. Advanced methods for physics-based modeling of the failures and faults in solid rocket motors and for novel anomaly detection techniques were studied in this project. These capabilities represent a critical subset of the technologies called for in this proposal. However, the goals of the IVHM project as expressed in this document are much broader than those identified thus far.

The objective of the Aviation System Monitoring and Modeling (ASMM) project, of NASA's former Aviation Safety and Security Program, was to develop technologies that would enable the aviation industry to take a more proactive approach to improving aviation safety through a process of identifying hazards and vulnerabilities, evaluating their causes, assessing risks, and implementing appropriate solutions to alleviate conditions that could compromise the safety of the system. As the ASMM project was concerned with the performance of the overall air transportation system, the faults and failures on which it focused tended to be in the areas of procedures and human communications with other human and non-human elements of the system. Nevertheless, the concepts of discovering unexpected vulnerabilities and gathering relevant evidence from diverse data sources to understand causal factors were influential in structuring the data mining and information analysis activities that underlie the IVHM approach.

Research Approach: The research approach described here is based on the fundamental requirements to develop safe and robust IVHM technologies that answer the four key challenges identified in the IVHM project goal. The cornerstone of this approach is robust methods to detect faults and failures at the aircraft level, to enable the diagnosis of those faults and failures, to estimate the remaining useful life (prognosis), and to fulfill the goal of automated mitigation. The milestones described in this section cover the Level 4 goal of IVHM.

Technology Validation Strategy: The verification and validation (V&V) of these technologies poses several major scientific and technological challenges. The development of adaptive reconfiguration technologies (which are still in the early stages of development) is at the heart of the mitigation strategy. Furthermore, while several generic software V&V strategies are available that would be applicable to various elements in the IVHM project, the emphasis at Level 4 would be the demonstration of validated technologies that meet the required false positive and false negative rates of the application area.

The validation tests for technologies at Levels 3 and 4 will be carried out on full-scale flights, subscale flight testbeds, and ground-based testing facilities available within NASA. The IVHM project will begin with a set of Adverse Events Types and candidate examples (listed in Table 2) that will focus the direction of the project. As the project matures and future technologies and trends become clear, this initial set of Adverse Events examples will change. The adverse events table will be evaluated and updated by the Systems Analysis and Research Test and Integration tasks at Level 4 to remain current with the trends in aviation; the particular adverse events targeted in IVHM technology evaluations will be selected and documented as part of the Research Test and Integration Plan. The five adverse event types in Table 2 are referred to in the milestones. The Validation Strategy will comprise extensive experimental testing and, where appropriate, Monte Carlo simulations, guided by the identified fault modes and relevant feature measures.

These events are categorized into five classes based on the overall remaining useful life of the affected system, subsystem, or component: incipient failures, slow-progression failures, intermittent faults, cascading faults and fast progression failures.

Adverse Event Type	Definition	Example Damage Condition
1. Incipient Faults	Hard to detect and differentiate due to extremely slow degradation in performance	1. Icing conditions in propulsion system 2. Fault of power electronics.

2. Slow Progression Fault	Very hard to detect, gradual degradation in performance	3. Fatigue cracks on metallic airframe structure 4. De-lamination in composites 5. Ball-jam in EMA
3. Intermittent Faults	Fault does not degrade but instead is a recurring hard fault that comes and goes, for example a signal conducted via a loose connector.	6. Wire chafing resulting in an electrical short due to an unexpected ground path
4. Cascading Fault	Faults that may have a single root cause yet progress to create faults in other systems, subsystems, or components.	7. Power system fault results in wide-spread systemic issues
5. Fast Progression Fault	Limited precursor signature but rapid degradation	8. Faults in Turbomachinery 9. Lightning and radiation related avionics fault 10. Software faults*

* Depending on the nature of the software fault, it could lead to a fast progression, as in the case of a stack overflow, or a slow progression, as in the case of a memory leak. Either way, a key challenge for IVHM is to develop methods to manage these sorts of faults.

Table 2. Adverse Events Table

Elements 4.1, 4.2, and 4.3 contain the project-level milestones for IVHM.

IVHM 4.1 Multidisciplinary IVHM Technologies, Tools, and Techniques			
Number	**Title**	**Year**	**Dependencies**
4.1.1	One ground-based test of detection, diagnosis, and prognosis for selected adverse event types (as specified in the Research Test and Integration Plan - RTIP) listed in Table 2.	FY11Q4	4.4.1, 4.4.2, 4.4.4, 3.1.1, 3.2.1, 3.3.1
Metrics	Baseline ground testing of detection, diagnosis, and prognosis methods. <u>Detection:</u> Measure false and true positive detection rates and area under a Receiver Operator Characteristic (ROC) curve, as appropriate, and the typical detection time constant for the incipient, slow progression, intermittent, cascading and fast progression faults listed in Table 2 covering at least two of the following subsystems: Airframe, Propulsion, and Aircraft Systems. Demonstrate a TBD improvement over the detection baseline established in 3.1.1. Improvement goal will be documented as part of RTIP and will be based on baseline, user		

	requirements and IVHM technology portfolio as established in Levels 1-3. <u>Diagnosis</u>: Measure false and true positive diagnosis rates and area under an appropriate ROC curve and the typical diagnosis time constant for the incipient, slow progression, intermittent, cascading and fast progression failures listed in Table 2 covering at least two of the following subsystems: Airframe, Propulsion, and Aircraft Systems. Demonstrate a TBD improvement over the diagnosis baseline established in 3.2.1 with diagnosis performed in concert with detection. Improvement goal will be documented as part of RTIP and will be based on baseline, user requirements and IVHM technology portfolio as established in Levels 1-3. <u>Prognosis</u>: Measure ability to estimate the remaining useful life (RUL) and prediction horizon from time of initial detection for elements for the incipient, slow progression, cascading, intermittent and fast progression failures in Table 2 covering at least two of the following subsystems: Airframe, Propulsion, and Aircraft Systems. Demonstrate a TBD improvement over the prognosis baseline established in 3.3.1 with life usage performed in concert with detection and diagnosis technologies. Improvement goal will be documented as part of RTIP and will be based on baseline, user requirements and IVHM technology portfolio as established in Levels 1-3.		
Metric Rationale	The methods drawn from the areas of detection, diagnosis, or prognosis should be available by FY11Q2. (i) The assessments for detection and diagnosis use false and true positive rates and the area under an ROC curve, as appropriate, for determining accuracy. We will also obtain the amount of time needed (time constant) for the baseline detection and diagnostic rates along with error bars on these quantities. We require that the detection and diagnostic methodologies be coupled. (ii) The baseline assessment for prognosis will be performed by estimating the RUL and prediction horizon via simulation. We require that the detection, diagnostic, and prognostic elements be coupled.		
4.1.2	One flight test of detection, diagnosis and prognosis technologies for selected adverse event types (as specified in the Research Test and Integration Plan) listed in Table 2.	FY12Q4	4.1.1, 4.4.4
Metrics	Flight testing of detection, diagnosis, and prognosis methods. (i) <u>Detection:</u> Measure false and true positive detection rates and area under a Receiver Operator Characteristic (ROC) curve, as appropriate, and the typical detection time constant for the incipient, slow progression, intermittent, cascading and fast progression failures listed in Table 2 covering at least two of the following subsystems: Airframe, Propulsion, and Aircraft Systems. Demonstrate at least equivalent detection performance in flight test to that established in 4.1.1. (ii) <u>Diagnosis</u>: Measure false and true positive diagnosis rates and area under an appropriate ROC curve and the typical diagnosis time constant for the incipient, slow progression, intermittent, cascading and fast progression		

	failures listed in Table 2 covering at least two of the following subsystems: Airframe, Propulsion, and Aircraft Systems. Demonstrate at least equivalent diagnosis performance in flight test to that established in 4.1.1 with diagnosis performed in concert with detection technologies. (iii) <u>Prognosis</u>: Measure ability to estimate the remaining useful life (RUL) and prediction horizon from time of initial detection for elements for the incipient, slow progression, intermittent, cascading and fast progression failures in Table 2 covering at least two of the following subsystems: Airframe, Propulsion, and Aircraft Systems. Demonstrate at least equivalent prognostic performance in flight test to that established in 4.1.1 with prognosis performed in concert with detection and diagnostic technologies.		
Metric Rationale	(i) Based on the results of the ground test in 4.1.1, we will assess detection and diagnosis technologies using false and true positive rates and the area under an ROC curve, as appropriate, for determining accuracy. (ii) Based on the results of the ground test in 4.1.1, the baseline assessment for prognosis will be performed by estimating the RUL and prediction horizon via simulation. We require that the detection, diagnostic, and prognostic elements be coupled.		
4.1.3	Documentation and public dissemination of IVHM technologies for research areas including detection, diagnosis, prognosis, and mitigation of specific damage conditions as outlined in Table 2.	FY08Q4 and each year thereafter	All IVHM Milestones
Metrics	Document and disseminate the research results through the submission of at least seven peer-reviewed journal articles, seven NASA Technical Manuscripts, and fourteen conference presentations. Disseminate results of at least five algorithms and five data sets via the Discovery and Systems Health Link (DASHlink), a website designed to enable the dissemination of data, algorithms, and papers. The DASHlink is discussed in IVHM 4.3.		
Metric Rationale	The documentation and dissemination through peer-reviewed journals and other venues is a critical deliverable of the IVHM project.		

IVHM 4.2 Systems Analysis for Health Management

IVHM focuses on addressing the requirements of future aircraft while maintaining a project-wide situational awareness of the issues arising from current and near-term aviation technology. The Systems Analysis task will have the responsibility to provide critical information to the IVHM management team regarding new technology trends as they pertain to the stated goal of the IVHM project. Thus, for example, new information regarding the development of NextGen, advances in materials science, aircraft related information technology, and the move towards more electric aircraft and other trends must be documented and disseminated through the project so that the project can make ‘course corrections’ to its research portfolio. As a Level 4 task, Systems Analysis is well positioned to provide knowledge to inform all aspects of the project regarding issues and circumstances that could affect the applicability of IVHM research.

Another main function of the Systems Analysis task will be to provide yearly updates and refinements to the Adverse Events Table (Table 2), thus providing a set of guiding requirements for IVHM technology evaluations that are occurring at all levels of the project. The Systems Analysis task will also continually assess the metrics within the milestones and provide guidance on potential updates as appropriate. As these Adverse Events are refined, the project can make modifications to the research plan to accommodate the changes.

The Systems Analysis task will draw heavily from data available from Aviation Safety Reporting System (ASRS), the Aviation Safety Information Analysis and Sharing (ASIAS), and the National Transportation Safety Board (NTSB) data sets along with several key data sources from NASA assets including data from the AirStar program, SAFETI lab, and the Icing Tunnel. The Systems Analysis task will take advantage of partnerships with external working groups and agencies such as the NASA Air Force Executive Research Committee, the Commercial Aviation Safety Team (CAST), DARPA, JPDO, and the NSF. An important source of information from within the Aeronautics Research Mission Directorate will be elements of the Fundamental Aeronautics Program.

In summary, the Systems Analysis task within IVHM will have two major responsibilities: (1) Assessment of future aviation trends as they pertain to IVHM research in the areas of detection, diagnosis, prognosis, and mitigation of adverse conditions in both hardware and software systems on aircraft and an associated update of Table 2, and (2) Dissemination of this information to the IVHM management team. The project-level milestones for Element IVHM 4.2 are described below.

IVHM 4.2 Systems Analysis for Health Management			
Number	**Title**	**Year**	**Dependencies**
4.2.1	Review statistical data and literature from academia, industry, and other government agencies to establish requirements for future work in detection, diagnosis, prognosis, and mitigation for hardware and software. (WAYPOINT)	FY08Q4 and Q4 of each subsequent year	

Outcome	1. Report and document the incidents and accidents related to the above research areas utilizing the most current statistical and prognostic data available from the ASIAS project. 2. Document and use data such as true and false positive rates for detection and diagnosis from the Joint Strike Fighter program and other relevant programs. 3. Focused assessment of the potential impact of JPDO Research and Development Plan /NextGen plans on IVHM. 4. Document reports by subject matter experts on future directions in the above research areas. 5. Assess future directions in aviation technology as related to IVHM topics through a report documenting the trends according to at least three conferences. 6. This milestone is considered a “Key Decision Point” to establish future requirements for the project. All Systems Analysis reports will be disseminated to the public through at least one peer-reviewed journal paper submission per year. 7. The Systems Analysis task may make recommendations that may influence project-wide milestones and metrics.		
4.2.2	Review statistical data and literature from academia, industry, and OGA to interpret and extract information about causal factors in current aircraft safety incidents and accidents and Failure Modes and Effects Analyses (FMEAs) which are related to the key research areas in IVHM. Develop a list of potential adverse conditions against which IVHM technologies can be evaluated. This list will be used to update Table 2. (WAYPOINT)	FY08Q4 and Q4 of each subsequent year	4.2.1
Outcome	Report and document the incidents and accidents related to the above research areas utilizing the most current statistical and prognostic data available from the ASIAS project. Assessment of all ‘baselines’ required in the project are to be completed in FY08Q4 with yearly refinement and updates as needed. This milestone is considered a “Key Decision Point” to establish future requirements for the project.		
4.2.3	Assessment of the state of the art in IVHM technologies as applicable to the specific adverse event type example conditions documented in Table 2. (WAYPOINT)	FY09Q2 and Q2 of each subsequent year	4.2.1, 4.2.2
Outcome	Report and document utilizing the most state of the art systems and technologies available. This milestone is considered a “Key Decision Point” to establish future requirements for the project.		
4.2.4	Assess IVHM research portfolio by mapping IVHM research to the potential adverse conditions as documented in Table 2. Identify overlooked safety issues that can be addressed through the key IVHM technologies. (WAYPOINT)	FY10Q4 Ongoing every two years	4.2.1, 4.2.2, 3.1.1, 3.2.1, 3.3.1, 3.4.1, 3.1.3, 3.2.3, 3.3.5, 3.4.2
Outcome	Produce one NASA Technical Manuscript that documents the IVHM technologies		

	developed and potential safety issues related to IVHM systems and technologies available. Portfolio analyses metrics are technical development risk, implementation risk, fatal accident rate, safety benefits/costs, and project impact of safety risk primarily for future systems. Note that this milestone depends on yearly progress demonstrations from the other elements in the project, thus fulfilling the aircraft-wide assessment requirement of the Systems Analysis element of the IVHM project.

IVHM 4.3 IVHM Discovery in Aeronautics Systems Health (DASHlink) Collaborative Website

The implementation and operation of a Discovery in Aeronautics Systems Health website (called DASHlink) will enable the collection of IVHM data, algorithms, and results and the dissemination of these to other NASA programs, other agencies, research institutions, and the public. DASHlink will serve as a national asset to enable collaborative research, and development and dissemination of open and public data, algorithms, and results for detection, diagnosis, prognosis, and mitigation of adverse events.

The DASHlink will become the "go-to" place for those who want to participate in IVHM research and development efforts. It will provide researchers easy access to large, multiple, and diverse data sets for the development and validation of advanced IVHM algorithms.

For NASA, internet social networking features provide new modes for disseminating data, results and knowledge to the public in an engaging way. For the public, the website creates an easily accessible environment for people to contribute to NASA’s mission. Using Web 2.0 features, users can collaborate in a range of ways, from simply adding tags to interesting content to providing expert interpretation of results via commenting.

We have three main goals for the website:

1. **Support collaboration for groups engaged in active NASA IVHM projects.**
   One of the primary activities the website will support is collaboration among NASA IVHM researchers across centers. Such collaboration requires an effective means for presenting results through text and graphics, soliciting feedback and engaging in open conversations. We plan to develop collaborative services and features including the ability to upload and view results, reports and other such content, and to download data. The website will also provide data version-tracking to avert data set inconsistency issues. Feedback and conversation will be facilitated by shared spaces for comments and responses. For instance, one user may post their own algorithm improvements or the results of a comparison between their algorithm and other standard approaches; another user may download data from a different center and contribute to another user’s algorithm development by providing the reference to a good paper on the topic in the comments section.
2. **Disseminate IVHM data, results and knowledge to a broader research community, as well as the general public.**
   In accordance with NPD 2200.1A, the IVHM project is committed to the dissemination of “scientific and technical information…for use by NASA, grantees, and, where appropriate,

the public." Dissemination and transparency add value by extending collaboration opportunities outside of NASA thus improving the cost effectiveness of NASA Research. The web, via the DASH*link* site, is an effective means of dissemination and advancing collaboration. Technical communities, including both academic researchers and industry R&D teams, will be served by having a single site relevant where content, e.g., data, project descriptions, open-source algorithms, results and related documentation, will be collected and disseminated. Members of these communities who are connected to the NASA ARMD IVHM project – recipients of NRAs and SBIR contracts, SAA partners or informal research partners – may become Registered Users of the site, once approved by a NASA civil servant. Registered Users will be allowed to contribute content, such as creating new pages and commenting on the pages created by other members. The general public will be able to view and download all information on the DASH*link* site, but will not be allowed to contribute content.

3. **Attract and inspire the next generation of scientists and engineers by presenting real world problems, relevant data and applicable tools.**
   For young people considering a technical career, the draw of the website will be the opportunity to work on real world problems and cutting edge algorithms. Initially we will target advanced students (graduate students and upper level undergrads) in technical disciplines. First, those with immediate connections to the IVHM project through NRAs and SAAs, and eventually with the broader aeronautics, engineering, and computer science academic departments. Collaborative Web 2.0 features may help involve these students.

The project-level milestones for Element IVHM 4.3 are described below.

IVHM 4.3 Discovery in Aeronautics Systems Health (DASHlink) Website			
Number	**Title**	**Year**	**Dependencies**
4.3.1	Implement and operate the Discovery in Aeronautics Systems Health Board (DASHlink) for internal NASA Ames use.	FY08Q2	
Metrics	Rollout NASA Ames internal version of the website with features for creating user accounts, creating home pages, uploading and accessing content. (20 registered users)		
Metric Rationale	We plan to demonstrate the capability to run the DASHlink internally to NASA Ames by FY08Q2 and support 20 Ames internal users.		
4.3.2	Implement DASHlink for dissemination of IVHM-related papers, publicly available data, and algorithms for both NASA internal and external members.	FY08Q4 and each following year.	4.3.1
Metrics	Develop a public website with at least 100 registered users by FY08Q4. For each following year, increase number of registered users by a factor of 2.		
Metric Rationale	We plan to demonstrate the capability to run the DASHlink as a public site in FY08Q3, and will build on the registered users from ARC-internal to at least 100 users by FY08Q4. The 100 registered users will be a combination of NASA civil servants, contractors, and NASA-affiliates, such as academic and industry partners. Standard site use metrics will		

	be collected using Urchin, a third-party software application.		
4.3.3	Document, via a submission to an appropriate peer-reviewed conference, the DASHlink case study, which will include the methodology and initial analysis of the collected metrics. (WAYPOINT)	FY08Q4	4.3.1, 4.3.2
Outcome	In order to ensure that the policies and procedures used for running the DASHlink meet and exceed the established methods in industry, this peer-reviewed conference presentation will provide sufficient detail to allow a peer-review of the methodology used. All policies (except for the security plan) will be posted on DASHlink for review and input by the community.		
4.3.4	Document, via a submission to an appropriate peer-reviewed journal, the methodology used to build, conduct and maintain the Discovery in Aeronautics Systems Health (DASHlink) website. (WAYPOINT)	FY09Q2	4.3.1, 4.3.2, 4.3.3
Outcome	To ensure that the policies and procedures used for running DASHlink meet and exceed the established methods in industry, the peer-reviewed journal article will provide sufficient detail to allow a peer-review of the method used. All policies (except for the security plan) will be posted on DASHlink for review and input by the community.		

IVHM 4.4 Research Test and Integration

The Research Test and Integration task has overall responsibility for the development of a plan for testing and integration of the research products developed in the IVHM project and the coordination of a working group to facilitate studies in IVHM systems integration and architecture issues. An IVHM system is more than just a set of IVHM technologies. The technologies must work together in a realistic environment and must provide significant safety improvements to justify the development, integration, and costs associated with these technologies.

This task has two main components. The first is the creation of a *Research Test and Integration Plan* that keeps track of significant IVHM test and evaluation activities. This planning and coordination effort is an important mechanism for understanding, demonstrating, and communicating the overall state and direction of the project. The second task is the establishment of an Integration Architecture and Assessment Strategy Working Group.

The Research Test and Integration Plan will formally track cross-project activities pertaining to IVHM testing. It provides traceability of requirements and directly contributes to construction of quantified project metrics. This task leverages the team’s rich capabilities in test planning, systems engineering, and analysis to ensure that the IVHM investment will result in measurable progress toward development of technologies that demonstrate the value of integrated vehicle health management. An integral part of the Research Test and Integration Plan will be to document established testbeds within NASA, other government agencies, and NRA/SBIR partners that would be useful for testing technologies developed in the program. To allow the project the flexibility to incorporate new testbeds that may become available through the course of the project, the RTIP will be a 'living document' that is updated as the need arises and provided formally to the project in Q2 and Q4 of each year. These new testbeds could be incorporated into the IVHM project elements for a variety of reasons including cost-effectiveness, new capabilities of the testbed, or joint cross-project or cross-program activities. Through collaboration with the Systems Analysis Task, this task provides the final assignment of the specific adverse events listed in Table 2 to the IVHM project.

The second component establishes an *Integration Architecture and Assessment Strategy Working Group* to facilitate sharing of information on integration and assessment among representatives from industry and other government agencies such as the Air Force and the FAA. Together, these efforts will result in a manageable and flexible integration approach for evaluating and demonstrating integrated capabilities while automating to the extent practical the generation of metrics for technology assessment. The Working Group will study the information exchange between the different subsystems and the system level which is essential for communication issues, synchronization, and input/output functionality.

A key activity of this Working Group will be to study and assess the fusion of health information from different subsystems and handling the associated uncertainties to provide an overall system level health assessment. These issues are critical to a successful implementation of system-wide IVHM technologies. Because of the significant resources required and implementation-specific issues that will arise in the development of a system-level reasoner, the project will leverage the expertise, tools, and technologies developed by partners in the Working Group. Initially, the critical topics this working group will cover include:

1. Assessment of at least two candidate IVHM System Architectures that would enablesystem level reasoning,
2. Development of requirements for a system level reasoner for health management technologies,
3. Assessment of techniques to manage and propagate uncertainty for diagnostics and prognostics and their impact of those techniques on system integration and architectures,
4. Assessment of asynchronous messaging and the development of standards for message passing for health management technologies,
5. Development and assessment of standards to address specific hardware and software integration issues.
6. Novel methods for testing and evaluating health management technologies,
7. Impact of IVHM architecture designs and approaches (distributed, centralized, hierarchical) on increasing safety,
8. Impact and potential value of large-scale sensor networks (wired, fiber optic, or wireless) in increasing safety
9. Value of self-healing and self-diagnostic avionics architectures (through redundancy, reconfiguration, or other means)
10. Assessment and cataloging of testbeds that that reside outside of the project and that could be used by the IVHM project. This information will be included in the Research Test and Integration Plan.

IVHM 4.4 Research Test and Integration

Number	**Title**	**Year**	**Dependencies**
4.4.1	Review current state of the art in integration of health management systems using information from academia, industry, and OGA to establish requirements for future work in systems integration for IVHM applications. (WAYPOINT)	FY09Q2 and Q2 of each subsequent year	4.2.1, 4.2.2, 4.2.3, 4.2.4
Outcome	1. Report and document the state of the art in system integration of health management systems utilizing the most current information available. 2. Document integration methodologies from the Joint Strike Fighter program and other relevant programs. 3. Focused assessment of the potential impact of JPDO IWP /NextGen plans on IVHM.		
4.4.2	Convene the Integration Architecture and Assessment Working group.	FY08Q4 Q4 for each year thereafter.	4.2.1, 4.2.2, 4.2.3, 4.2.4, 4.4.1
Outcome	The Integration Architecture and Assessment working group shall contain at least 3 members within the NASA Aeronautics Research Mission Directorate (but outside of the IVHM project), 3 members from academia, 3 members from industry, and 3 members from other government agencies, and at least 6 members from the IVHM project. This group will provide recommendations to the IVHM project but has no authority over it or other NASA activities.		
Metric Rationale	The active participation from multiple partners within and outside of NASA will help ensure the success of this working group and the success of the Research Test and Integration Plan.		
4.4.3	Document the findings of the Integration Architecture and Assessment Working Group. (WAYPOINT)	FY10Q4	4.2.1, 4.2.2, 4.2.3, 4.2.4, 4.4.1, 4.4.2, 4.4.4
Outcome	Report and document a method for systems integration that utilizes the most recent data and procedures for integrated systems health management available. This milestone is considered a “Key Decision Point” to establish future requirements for the project. The report shall be published in an appropriate peer-reviewed conference or journal.		
4.4.4	Develop IVHM research test and integration strategy. This will be identified as the Research Test and Integration plan and will be updated yearly. The RTIP provides the final assignment of Table 2 adverse events for the IVHM project. (WAYPOINT)	FY08Q4 Then Q2 and Q4 for each year thereafter.	4.2.1, 4.2.2, 4.2.3, 4.2.4, 4.4.1, 4.4.3, 3.5.2
Outcome	The Research Test and Integration Plan will be updated every two quarters to provide the IVHM project with information regarding new testbeds, test opportunities. The annual Q4 deliverable will include a final update of the Adverse Events Table (Table 2) and an update to the Software Section of the Adverse Events Table.		

Level 3 – Theme Research

The following are statements of the problems and the approaches to their solutions for the five themes of Level 3: detection, diagnosis, prognosis, mitigation and integrity assurance. Each thematic element is responsible for the creation and formation of the research plans for that area. These research themes are designed to directly support the goal of the IVHM project. The Associate Principal Investigators reside at Level 3.

IVHM 3.1 Detection

Problem Statement: Adverse events can lead to potentially serious consequences if they go undetected. The goal of the Detection element is to develop validated technologies to detect anomalies from adverse events throughout the aircraft in hardware and in software, and the interactions between these two classes of systems. Information regarding the ongoing state of health of the aircraft, including anomaly detection, can be passed to the diagnosis technology to enable the rapid isolation and severity classification of the possible anomalous events. This information could also flow to prognosis technology to estimate the remaining useful life of the affected system or component. Finally the mitigation of the results of adverse events or declining state of system health can be carried out as appropriate. At Level 3, this element emphasizes the integration of novel sensor technologies for structures, propulsion systems, and other subsystems within the aircraft. This element relies on technologies developed at Levels 1 and 2, including:

- capabilities that allow for the detection of hardware and software faults;
- capabilities that allow for the development and application of complete sensor systems throughout the aircraft;
- characterizing, quantifying, and interpreting multi-sensor outputs;
- integration of propulsion, airframe, and aircraft health information for improved vehicle wide state-awareness;
- developing sensors that operate in extreme environments and novel sensory materials; and
- developing new methods to provide better and more accurate information to diagnostic computational algorithms that reconstruct damage fields from sensor values.

Research Approach: The research approach develops a set of validated technologies that detect adverse event and health status by integrating the validated detection capabilities developed for the major systems in an aircraft, including the Airframe, Propulsion, and Aircraft Systems (and associated subsystems) research areas at Level 2. This area emphasizes anomaly and state characterization and quantification through the use of sensor and sensory material technology, high temperature sensing technologies, and novel methods to detect failures in electrical, electromechanical, electronic, and software systems. A complete system approach will be implemented across the vehicle and within the sensor system itself to improve factors such as reliability, ease of implementation, and ability to cross correlate data. Where possible, a rigorous mathematical framework will be employed to ensure the detection rates are acceptable with appropriate false-positive and true-positive rates as characterized by the area under an appropriate receiver-operator characteristic (ROC) curve.

IVHM 3.1 Detection			
Number	**Title**	**Year**	**Dependencies**
3.1.1	Baseline assessment of detection capabilities at the subsystem or component level for RTIP-specified Table 2 conditions* using assessments from the literature, testbeds, and/or simulations. (WAYPOINT)	FY09Q2	4.4.4
Outcome	Obtain, via appropriate testing, a baseline measurement of false and true positive detection rates and area under a Receiver Operator Characteristic (ROC) curve, as appropriate, and the typical detection time constant for selected failure types in Table 2. Measure the tradeoff between the detection time constant and the area under the ROC curve as appropriate. For those sensors for which ROC-based analysis is not appropriate, we will document the appropriate detection performance metrics for use in future milestones. *Note: the RTIP will contain a description of the testbeds needed to perform the tests on each element of Table 2.		
3.1.2	Assessment of validated demonstrations of detection of at least 3 out of the 5 adverse event types listed in Table 2 (as specified in the RTIP) with performance improvements as listed below.	FY09Q2 FY10Q2 FY11Q2	4.4.4, 3.1.1. 2.2.1.1, 2.3.1.1, 2.3.1.2, 2.3.1.3
Metrics	(i) Create a ranked detection portfolio (with down-selection as needed) in terms of the performance metrics listed in (ii) and document findings in at least one NASA technical publication. (FY09Q2). (ii) Maximin: The anomaly detection methods built in the IVHM project each will be measured using either 1) The area under the ROC curve to measure the detection rate and the detection time constant or 2) Another sensor performance measure as identified in 3.1.1. For the methods that have the poorest performance with respect to these metrics, this milestone is designed to show at least 15% improvement in detection performance for the lowest performing method. The baseline detection rates and time horizons will be determined in 3.1.1. Submit at least one peer-reviewed journal article documenting the results of the research. (FY10Q2) (iii) Demonstration of anomaly detection capabilities such that detection occurs with 25% improvement in detection time horizon (or appropriate sensor performance measure) for a specific subset of the adverse event types listed in Table 2 with at least 20% improvement in detection rate (accuracy or appropriate sensor performance measure) for that subset of adverse events. Submit at least one peer-reviewed journal article documenting the results of the research. (FY11Q2)		
Metric Rationale	The baseline time horizon and detection rate or other appropriate performance measures will be set in 3.1.1. The ROC curve and time horizons are standard measures of detection accuracy and detection speed. Other performance measures will be defined and baselined, as needed, in 3.1.1. The ‘Maximin’ portion of the milestone maximizes the minimum performer with respect to the appropriate detection performance metric.		
3.1.3	An anomaly detection method that has the ability to detect at least 3 known anomalies in real or emulated data of large, fleetwide heterogeneous data sources.	FY12Q2	1.3.1.1, 1.3.1.2, 1.3.3.1, 1.3.5.1, 1.3.5.2
Metrics	A demonstration of the capability will reliably detect at least 3 anomalies of varying levels of atypicality that are known to exist in a given data set. The reliability of the		

	anomaly-detection capability will be set using the metrics established in 1.3.3.1 and will show a 10% improvement compared to a standard benchmark set in 1.3.3.1. The size of the data set must be at least 10 TB and the anomalies may be either known anomalies in real flight-recorded data or artificially injected anomalies into representative data sets.
Metric Rationale	The results of the analyses using this automated capability must be deemed reliable by aviation domain experts for this tool to be considered for support of ASIAS.

IVHM 3.2 Diagnosis

Problem Statement: The goal of the Diagnosis element is to develop integrated and validated technologies to determine the causal factors, the nature and severity of an adverse event and to distinguish that event within a family of potential adverse events. This diagnostic capability goes beyond standard fault isolation techniques and relies on the Detection element to provide evidence of the anomaly. At Level 3, this element emphasizes the integration of mathematically rigorous diagnostic technologies that are applicable to airframe structures, propulsion systems, software, avionics and other subsystems within the aircraft. Technologies used must be able to perform diagnosis given heterogeneous and asynchronous signals coming from the health management components of the vehicle and integrating information from each of these components. Thus, the ability to actively query health management systems, use advanced decision making techniques to perform the diagnosis, and then to assess the severity using these techniques is a critical component of the project. The mathematical rigor of the diagnosis and severity assessment will be treated through modeling and analysis methods and a Bayesian methodology which allows for the characterization and propagation of uncertainties through models of aircraft-wide failure and degradation. *Both computational and hardware implementations of these diagnostic capabilities are essential for the success of this element.*

Research Approach: The diagnostic capabilities in this element will be performed using Bayesian and other methods that appropriately model the uncertainties in the subsystem due to aerodynamic loads, mechanical and electrical noise and other sources of uncertainty inherent in the process of detection. The ability to actively query the underlying health management systems (whether they are related to detection or not) is critical to reducing the uncertainty in the diagnosis. Thus, for example, if there is ambiguity in the diagnosis about the type and location of a particular failure in the aircraft structure, the diagnostic engine should be able to actively query that system or related systems in order to determine the most probable location and severity of the anomaly. This research challenge will only be met by advancements in decision and diagnostic science as applied to the health management systems of an aircraft. Where possible, a rigorous mathematical framework will be employed to provide a rank ordered list of diagnoses, an assessment of the severity of each diagnosed event, and a measure of the certainty in the diagnosis. This information will be crucial for prognostics and the assessment of the remaining useful life of the affected systems and components, as well as for decision-making processes to mitigate risk.

IVHM 3.2 Diagnosis			
Number	**Title**	**Year**	**Dependencies**

3.2.1	Baseline assessment of automated diagnosis capabilities at the subsystem or component level RTIP-specified Table 2 conditions using assessments from the literature, testbeds, and/or simulations. (WAYPOINT)	FY09Q2	4.4.4
Metrics	Obtain a baseline measurement of the false and true positive diagnosis rates, area under an appropriate ROC curve, and the typical diagnosis time constant for selected failures in Table 2. Identify the tradeoffs between detection time, area under the ROC curve, and system complexity measures required to achieve given levels of accuracy. Include an assessment of ability to disambiguate multiple competing diagnoses.		
Metric Rationale	The baseline assessment for diagnosis uses false and true positive rates and the area under an appropriate ROC curve for determining accuracy. We will also obtain the amount of time needed (time constant) for the baseline diagnostic rates along with error bars on these quantities.		
3.2.2	Assessment of validated demonstration of diagnosis of at least 3 out of the 5 adverse event types listed in Table 2 (as specified in the RTIP) with performance improvements as specified below.	FY09Q2 FY10Q2 FY11Q2	4.4.4, 3.2.1, 2.1.2.1, 2.1.2.2, 2.2.2.1, 2.3.2.1
Metrics	(i) Create a ranked diagnosis portfolio (with down-selection as needed) and document findings in at least one NASA technical publication. (FY09Q2) (ii) Maximin: Verify demonstration of at least a 20% improvement in the diagnosis time constant and a 15% improvement in diagnosis rate for the minimum performing diagnosis mechanism in the IVHM Diagnosis portfolio. Submit at least one peer-reviewed journal article documenting the results of the research. (FY10Q2) (iii) Demonstration of diagnosis capabilities such that diagnosis occurs with 25% improvement within the time constant for a subset of the adverse event types listed in Table 2 with at least 20% improvement in diagnosis rate as measured by an appropriate ROC curve compared with the baselines set in 3.2.1. Submit at least one peer-reviewed journal article documenting the results of the research. (FY11Q2)		
Metric Rationale	The diagnosis methods built in the IVHM project each will be measured using at least two metrics: area under ROC curve to measure diagnosis rate, and the diagnosis time constant. For the methods that have the poorest performance with respect to these metrics, this milestone is designed to provide improvement for the lowest performing method. The baseline diagnosis rates and time constant will be determined in 3.2.1. This so called 'Maximin' portion of the milestone maximizes the minimum performer with respect to the diagnosis performance metrics.		
3.2.3	Demonstration of disambiguation of faults in a subsystem	FY11Q2	3.2.1
Metrics	Given a fixed sensor suite and diagnosis time constant, demonstrate ability to disambiguate 90% of potential faults in a subsystem. Submit at least one peer-reviewed journal article documenting the results of the research.		
Metric Rationale	Disambiguation of multiple competing diagnoses within a given time constant (and for a given sensor suite) is critical to the success of an IVHM diagnosis system.		
3.2.4	An automated capability to diagnose the causal factors of anomalous operations in real or emulated data of large, fleet-wide or airspace heterogeneous	FY12Q2	1.3.1.1, 1.3.1.2, 1.3.3.1, 1.3.5.1, 1.3.5.2

	data sources.		
Metrics	A demonstration of the capability will provide reasonable possibilities of the causal factors entailed in at least 3 anomalies of varying levels of atypicality that have been identified in a given data set. The anomaly diagnosis capability will be measured using the area under the ROC curve to measure the rate of diagnosis of causal factors to show the ability to disambiguate diagnoses in least 2/3 of the events with sufficient certainty to indicate the correct course of action. The size of the data set must be at least 10 TB and the anomalies may be either known anomalies in real flight-recorded data or artificially injected anomalies into representative data sets.		
Metric Rationale	Having detected a potential safety problem, it is essential that the causal factors be well understood in order to prescribe the most appropriate intervention or mitigation. `The results of the analyses using this automated capability must be deemed reliable by aviation domain experts for this tool to be considered for support of ASIAS.		

IVHM 3.3 Prognosis

Problem Statement: The goal the Prognosis element is to determine, given the information from the detection and diagnosis health management systems and other systems, a validated estimate (i.e., with a measure of confidence) of the remaining useful life of the candidate failures generated by the diagnosis element. The prognostic element relies on advanced physical models of the propagation of known failures through materials, propulsion systems, and aircraft systems in order to provide an assessment of the remaining useful life (RUL) of applicable items listed on the Potential Adverse Events List. The assessment of the RUL can be used by tools and technologies developed in the IRAC project to place additional restrictions such as a new operating envelope on the flight control systems. We will seek and incorporate relevant information from the MDAO IDG in the Fundamental Aeronautics Program to establish the appropriate level of fidelity of physics-based models. These physics based models must be computationally efficient so that they can execute in an onboard environment and also properly handle the uncertainties that arise from the detection and diagnosis health management systems. Data-driven models will be used, where suitable, to emulate physics-based models to reduce the computational time required to estimate the propagation of damage through the system. Mathematical bounds on the estimates of the remaining useful life and the estimated certainty will be provided where possible. At Level 3, this element includes integration of information from the various systems in the aircraft as well as examination of fleet-wide or airspace-wide data to predict anomalies pertaining to the National Airspace System.

Research Approach: We will develop an aircraft-level capability to predict the remaining useful life of affected components for the major subsystems included in the Airframe, Propulsion, and Aircraft Systems research areas at Level 2. The research will develop methods for making predictions, examine the representation and management of uncertainties in such predictions, and establish an assessment methodology for comprehensive and objective evaluation of prognostics algorithm performance. The technical approaches for prognosis will include developing physics-based models of damage propagation, data-driven approaches when run-to-failure data is available, and extensions of statistical life usage or reliability models as appropriate. The sources of uncertainty in remaining useful life estimates will be investigated along with effective means to represent and manage them so as to make the predictions useful to the intended recipient. A rigorous mathematical framework will be employed to characterize the predictions and confidence in those predictions using relevant metrics, including but not limited to the accuracy and precision of remaining useful life estimates as measured for tests conducted via simulation or other test beds.

IVHM 3.3 Prognosis			
Number	**Title**	**Year**	**Dependencies**
3.3.1	Baseline assessment of automated prognosis capabilities at the subsystem or component level for RTIP-specified Table 2 conditions using assessments from the literature, prognostic testbeds, and/or simulations. (WAYPOINT)	FY09Q4	4.4.4
Outcome	Report delineating baseline prognostic performance on selected (or comparable) failures in Table 2.		
3.3.2	Guidelines for fidelity of prognostic estimates. (WAYPOINT)	FY09Q4	3.3.1, 1.2.3.7
Outcome	This waypoint will produce documentation in the form of a peer-reviewed journal article or NASA TM that describes the appropriate level of fidelity for physics-based models for prognostics on subsystems and components.		
3.3.3	Methodology for assessing the performance of prognostic algorithms and methods. (WAYPOINT)	FY09Q4	3.3.1, 1.2.3.6
Outcome	This waypoint will produce documentation in the form of the submission of a peer-reviewed journal article that describes a rigorous statistical methodology for assessing the quality of prognostic algorithms.		
3.3.4	Forecasting technology that has the ability to predict at least 3 known anomalies in real or emulated data of large, fleetwide heterogeneous data sources.	FY12Q2	1.3.1.1, 1.3.1.2, 1.3.5.1, 1.3.5.2
Metrics	A demonstration of the capability will predict the probability of future occurrence of at least 3 prescribed anomalous operations of varying levels of frequencies of occurrence across fleets of aircraft or across the airspace using real or emulated data. The ability to forecast known anomalies will be measured by computing the time difference between the forecast of the first occurrence of an anomaly and the actual occurrence of that anomaly. The forecasting horizon (or other appropriate metric as determined in 1.3.1.1) will be improved by 10% compared to the standard benchmark. The size of the data set must be at least 10 TB and the anomalies may be either known anomalies in real flight-recorded data or artificially injected anomalies into representative data sets.		
Metric Rationale	The results of the analyses using this automated capability must be deemed reliable by aviation domain experts for this tool to be considered for support of ASIAS.		
3.3.5	Assessment of the ability to perform prognostic reasoning for at least four of the adverse events listed in Table 2 (as specified in the RTIP) with performance improvements as specified below.	FY09Q2 FY10Q4 FY12Q2	4.4.4, 3.3.1, 2.1.3.1,2.2.3.1, 2.3.3.1, 1.2.3.5
Metrics	(i) Ranked prognosis portfolio (with down-selection as needed) and document findings in at least one NASA technical publication. (FY09Q2) (ii) Maximin: The prognostic algorithms built in the IVHM project each will be		

	measured using the estimated remaining useful life as a metric of performance. For the methods that have the poorest performance with respect to this metric, this milestone is designed to improve the lowest performing method. The baseline accuracy rates will be determined in 3.3.1. Verify demonstration of at least a 15% improvement in estimation of the remaining useful life for the minimum performing prognostic method in the IVHM prognosis portfolio. Submit at least one peer-reviewed journal article documenting the results of the research. (FY10Q4) (iii) The creation of a prognostic reasoning technology that can differentiate, disambiguate, and estimate the remaining useful life of at least four of the adverse events listed in Table 2 will be demonstrated. The baseline accuracy rates will be determined in 3.3.1. Submit at least one peer-reviewed journal article documenting the results of the research. (FY12Q2)
Metric Rationale	Estimated remaining useful life is a metric used for prognosis. The baseline time horizon and prediction accuracy will be set in 3.3.1. The estimated remaining useful life is a metric used for prognosis. The baseline time horizon and prediction accuracy will be set in 3.3.1. The ‘Maximin’ portion of the milestone maximizes the minimum performer with respect to this metric.

IVHM 3.4 Mitigation

Problem Statement: The goal of the Mitigation element is to develop onboard mitigation technologies to minimize the impact of adverse effects, as identified by deployed IVHM detection, diagnosis, and prognosis systems, to ensure continued safe flight and/or landing of the aircraft. As noted in Table 2, these adverse events could include anomalies, faults, malfunctions, failures, and damage that occur as a result of aircraft operation in harsh environments, discrete source damage, design faults (both hardware and software), or wear and degradation that will manifest/escalate during flight and affect in-flight performance of aircraft systems, propulsion, and/or structure.

Onboard Mitigation Technologies: This element has two areas of focus: spanning the most important gaps in current capabilities and developing techniques to enable adaptive reconfiguration and redundancy management techniques to mitigate software malfunctions. Where possible, a rigorous mathematical framework will ensure that the developed technologies can be validated and verified and that the methods used are robust and are implementable within an appropriate time horizon. Mitigation in the context of self-healing materials involves either the restoration of some or all of the load-bearing capability of a structure under monotonic loading or the reduction in the rate of damage accumulation under cyclic loading. Materials that are capable of self-healing incipient damage states will be of great benefit in environments and conditions where access for manual repair is limited or impossible, or where damage may not be detected. Structures made of healing composite materials may have significantly prolonged service life and improved safety and reliability. New design and analysis methodologies will be developed to fully exploit the benefits of both types of healing material systems.

Adaptive technologies that enable the automatic reconfiguration, redundancy management, and control of subsystems in the event of a malfunction, fault, and/or failure in one or more subsystems are an important part of the research portfolio. This research does not include the development of adaptive control technologies for effectors, control surfaces, and engines as that is an area of research in the IRAC project. However, collaboration with the IRAC Project to integrate IVHM detection, diagnosis, and prognosis technologies with IRAC adaptive controls technologies will be pursued as a focus area for mitigation of onboard failures and damage. This research will enable the development of requirements and technologies for managing and controlling systems interaction issues, and mitigating onboard failure and damage to maintain an acceptable level of in-flight safety and performance. Under this inter-Project collaboration, mitigation could entail changing the operation of the aircraft to minimize the loading or the dependency on the critical element so as to enable continuation of flight to a safe landing.

IVHM 3.4 Mitigation			
Number	**Title**	**Year**	**Dependencies**
3.4.1	Establishment of minimum performance criteria of candidate mitigation strategies at the subsystem or component level for selected conditions from Table 2 (as specified in RTIP) based on a survey of user requirements. (WAYPOINT)	FY09Q2	
Outcome	Submit a paper in a peer-reviewed conference or journal describing the baseline mitigation performance on selected conditions from Table 2.		
3.4.2	Assessment of validated demonstration of mitigation technologies for at least two events listed in Table 2 (as specified by RTIP).	FY10Q2	3.4.1, 2.1.4.1, 2.2.4.1, 2.2.4.2, 2.2.4.3, 2.4.4.1
Metrics	The assessment will show, for the subject fault / failure scenarios, that the employed mitigation technologies meet or exceed the minimum required performance criteria as established in 3.4.1. Document results via the submission of at least one peer-reviewed journal article.		
Metric Rationale	The minimum performance criteria will be set in 3.4.1.		

IVHM 3.5 Integrity Assurance

Problem Statement: The goal of the Integrity Assurance element is to develop advanced integrity assurance tools, testbeds, and technologies for assessing the performance, robustness, and other integrity assurance needs required for the safe deployment of IVHM systems. These new integrity assurance tools and techniques will be developed in a manner mindful of complementary activities underway within multi-agency R&D programs and will seek to address software deployment barriers for NextGen. Example activities in this area include employing design integrity tools that preclude certain faults due to design errors resulting from ambiguous or inconsistent requirements, designs that ensure certain faults cannot propagate outside of software or hardware partitions, providing proofs that show critical architecture designs are correct with respect to safety and operational requirements, and identifying violations of critical safety properties post-deployment.

Research Approach: Understanding and addressing IVHM system integration, design and operational integrity issues will be a critical component of this research element. To this end, the Integrity Assurance research area will focus on the investigation, development, and demonstration of tools, techniques, and methodologies for assuring design and processing integrity of flight critical systems. Mathematically rigorous techniques and tools for the specification, design, and verification of IVHM software systems are needed, and will include advancements in symbolic model checking, theorem proving, compositional verification, static analysis, and runtime integrity monitoring. In civil aviation, DO-178B "Software Considerations in Airborne Systems and Equipment Certification" provides the accepted guidance for certifying all new software. New V&V and safety assessment guidelines will be needed for the envisioned IVHM software development techniques that are not currently permitted under DO-178B. These new guidelines will be based, in part, on the analysis of safety-case approaches for the assurance of software intensive systems, the development of specific safety cases for relevant IVHM systems, and the deployment of assessment frameworks that identify inconsistencies between observed system behavior and its associated dependability case.

Extensive testing of new IVHM technologies and systems will be necessary not only for demonstrating their benefits to aviation safety, but to also provide a level of assurance that the new technologies and systems are themselves constructed in a safe manner. Experimental validation methods are needed that can encompass medium to large-scale integration of aircraft systems and subsystems, with the potential for insights gained to scale to even larger scales such as airspace concepts of operation.

The Airborne Subscale Transport Aircraft Research (AirSTAR) testbed provides a unique platform for validation of in-flight health assessment technologies that cannot be safely flight validated with full-scale vehicles, and will provide for a variety of in-flight damage injection scenarios that include: off-nominal control surface trim, sensor failure, asymmetric thrust, and in-flight structural failure. Moreover, the platform provides for collection and archiving of flight data, including both nominal flights and flights subjected to fault injection, over multiple flights for long-term trending analysis.

In addition, there will be a focus on development of simulation and hardware-in-the-loop testbeds for testing IVHM technologies, and integration of selected IVHM technologies into a simulation/hardware-in-the-loop testbeds to assess system/coupled-systems performance in terms of accuracy, reliability, and robustness. Structural failure due to crack propagation and/or design limit exceedance has been cited as a causal factor in several accidents. A ground-based, closed-loop testbed capability will be developed that integrates flight simulations, flight profile dynamics loading models, and airframe structures testing facilities. This testbed will provide for the assessment of airframe health management and damage mitigation concepts within a realistic operational environment that will include the capability to impose adverse flight conditions such as atmospheric turbulence. Integration methods will be developed and may be achieved by means of a simplified load/displacement mapping for an element-size test specimen (possibly a simple stiffened or unstiffened panel with an initial flaw) subjected to induced loads (using a servo-hydraulic test frame) as a function of flight simulator outputs. As the damage begins to propagate, the diagnosis and prognosis algorithms (from the IVHM project) will be integrated with mitigation and control techniques (from the IRAC project) and exercised. This relatively simplistic configuration will provide an effective test bed for validating new sensors, damage diagnosis and prognosis algorithms, and mitigation techniques, in addition to providing in-flight input for the control system. More complex configurations can be considered over time. The Level 3 milestones are described below.

IVHM 3.5 Integrity Assurance			
Number	**Title**	**Year**	**Dependencies**
3.5.1	Baseline assessment and prioritization of IVHM verification and validation enabling capabilities at the subsystem or component level. (WAYPOINT)	FY09Q2	4.4.4
Outcome	Submit at least one NASA Technical Publication describing the baseline integrity assurance capabilities, including those in verification and validation, to address selected conditions in Table 2.		
3.5.2	Demonstrate plausibility of at least 80% of the testbeds required in the RTIP: a plausible testbed can meet 95% of the RTIP-specified requirements listed for that testbed.	FY12Q2	3.5.1
Metrics	The Research Test and Integration Plan will contain the testing requirements for the IVHM project and the Integration Plan. This milestone is designed to show that 80% of the testbeds required in the RTIP exist or can be developed. Each viable testbed must meet at least 95% of the documented requirements.		
Metric Rationale	The RTIP will require a number of testbeds which will be generated by the Integrity Assurance element of IVHM. This milestone requires that a significant proportion of the testbeds are created within the documented requirements.		

Level 2 – Discipline Level Research

The following are statements of the problems and the solutions approaches for the four elements of the Discipline level research at Level 2. Element IVHM 2.1 addresses Aircraft System Health Management, IVHM 2.2 addresses Airframe Health Management, IVHM 2.3 addresses Propulsion Health Management, and IVHM 2.4 addresses Software Health Management. The Level 2 milestones are described for each of these four elements.

IVHM 2.1 Aircraft Systems Health Management

Problem Statement: The goal of the Aircraft Systems Health Management element of the IVHM project is to develop methods that will enable detection, diagnostics, prognostics, and mitigation strategies for systems, including but not limited to electromechanical systems, avionics, electrical power systems, and electronics. The vast number of life-limited subsystems, components, and unique parts that need to be covered is a significant challenge for aircraft systems health management. Given the relatively low cost of some of the aircraft subsystem components, it is often cheaper to use these systems until they fail and to replace them without further troubleshooting, assuming that there will be enough redundancy or performance margin to maintain safety. However, that assumption sometimes fails to hold and simple failures of aircraft subsystems may yield catastrophic results, especially for highly integrated systems. Since it is impractical to conduct health management research on all possible aircraft components and subsystems, the research will focus on those elements which provide critical functionality for the safe operation of the aircraft. Furthermore, particular attention will be paid to those aspects which are forward looking, such as the use of electromechanical actuators, pervasive power semiconductor and digital devices, and hybrid DC and AC power management and distribution systems.

Research Approach: Research will be conducted to develop health management technologies, methods, and tools pertinent to safety-critical aircraft components, subsystems, and assemblies. The proposed approach is to address the knowledge needed to understand faults, failures, their impacts on aircraft health, and mitigation actions to restore lost functionality. Precursors to catastrophic system failures may involve subtle and complex interactions between mechanical and electrical components, for example, and the operational and environmental conditions in which they function. Thus, validation of IVHM technologies will occur in high-fidelity, relevant environments to the extent possible and will incorporate fundamental research in uncertainty representation and management to specify confidences along with estimations of remaining useful life.

One focus area of research within the Aircraft Systems Health Management element will be electro-mechanical actuators (EMA). They are presently used in numerous aerospace applications, from robotic applications to thrust vector control of rocket engines, where they accomplish a range of rotational and translational functions. There is an increasing tendency to move to all-electric aircraft and spacecraft designs (i.e., without any hydraulic systems), so even more widespread use is likely in the future. The application that this research focuses on is aircraft flight control systems. Such systems are critical for flight safety and must not only provide a high level of reliability, but also a significant degree of fault tolerance. Incorporation of health management technologies for EMAs will be instrumental to achieving those objectives. To make such health management systems feasible, this work will concentrate on the following research goals: detect and classify incipient fault conditions; reliably estimate remaining useful life (RUL) for both nominal and degraded operating regimes; generate real-time actions or recommendations for extension of RUL with changes in the operation modes or environment; and, at any point during its lifetime, provide an accurate picture of EMA component health to maintenance crews, enabling on-demand, selective servicing.

Another focus area within Aircraft Systems Health Management will be on electronic components. These components have an increasingly critical role in on-board, autonomous functions for vehicle controls, communications, navigation, etc. However, the assumption of new functionality will also increase the number of electronics faults with perhaps unanticipated fault modes. In addition, the move toward lead-free electronics and MEMS will further result in unknown behavior. Therefore, an understanding of the behavior of deteriorated components is needed as well as the capability to anticipate failures and predict the remaining life of embedded electronics. This research will establish an electronics degradation testbed to investigate the degradation characteristics of power semiconductor components and to identify failure precursors. Physics of failure models will be developed and applied along with data-driven and statistical lifing models to estimate the remaining useful life of electronics.

An additional focus area will examine the direct and indirect effects of lightning and non-ionizing radiation on avionics in composite-based aircraft. As the use of composite materials continues to increase, the effects of lightning and the resulting high intensity radiated fields (HIRF) become significant risks to avionics because of the reduced dissipation of electrical energy afforded by composites. Similarly, the lower density of composite materials reduces their effectiveness in protecting against non-ionizing radiation. Avionics systems may also be susceptible to upsets from ionizing radiation due to the bombardment of atmospheric neutrons on critical processing or memory areas. Research will be conducted to detect when such upsets have occurred and develop techniques to mitigate their effects. Commercial-grade avionics hardware will be integrated with ground based and sub-scale test platforms for closed-loop experiments involving induced disturbances for purposes of evaluating the effectiveness of upset detection and adaptive recovery and redundancy management strategies for guidance, navigation, and control systems.

A focus area for work in electrical systems includes power management and distribution systems that employ multiple voltage levels for hybrid DC and AC systems, power converters, electric drives, and control electronics. Techniques for intelligent health management and control of advanced electrical power systems will be developed and verified in simulations and hardware-in-the-loop testing. One of the challenges in Electrical Power Systems (EPS) health management is that signals and faults manifest themselves in continuous, discrete, and transient domains. Thus, no single fault detection methodology is sufficient to cover a broad range of EPS failures. This makes EPS an ideal testbed for the development of hybrid reasoning methods based on continuous and discrete models of a physical system. A testbed will be used to develop Bayesian sensor fusion tools for robust state estimation and sensor failure detection and to develop and refine model-based and hybrid diagnosis tools.

IVHM 2.1 Aircraft Systems			
Number	**Title**	**Year**	**Dependencies**
2.1.2.1	Validated methodologies and tools for the diagnosis of failures associated with aircraft components and subsystems implicated by the adverse events in Table 2.	FY11Q2	4.2.1, 1.2.2.2, 1.2.2.3
Metrics	Using appropriate diagnostic testbeds, demonstrate validated diagnosis of at least 3 of the 5 fault types (incipient, slow progression, fast progression, cascading, intermittent) using Bayesian and hybrid reasoning techniques to greater than 95% accuracy.		
Metric Rationale	Diagnostic algorithms must deal with a wide range of fault behavior; some techniques may deal with particular faults more effectively than others. The accuracy metric is notional and will be informed by the systems analysis tasks and the benchmarking activity in 1.2.2.2.		
2.1.2.2	Tools and techniques to conduct experiments to establish baseline parameters and asses user requirements for direct and indirect effects of lightning.	FY11Q2	1.1.1.9, 1.1.2.1
Metrics	(i) Develop capabilities to conduct lightning surface current measurements in both time and		

	frequency domains on at least 5 composite materials, including one or more with embedded conducting mesh, to establish baseline parameters. Characterize the current and voltage components within 10% of peak values, using Voltage Waveforms A and D as specified in RTCA\DO-160F Section 23. (ii) Compare results with user requirements and submit one peer-reviewed publication summarizing results. (iii) Characterize at least 3 conditions under which a composite structure sustains each of the following types of damage: immediate, short-term, and long-term damage. (iv) Quantify the mean-time to failure of a composite structure as a function of surface current for immediate, short-term, and long-term damage within 10% of the true value.		
Metric Rationale	Direct effects include damage for cases in which the structure sustains immediate damage, as well as changes to structural characteristics (diagnosis) and their long-term impact (prognosis) for cases in which explicit damage is not evident.		
2.1.3.1	Validated methodologies and tools for the prognosis of failures associated with aircraft components and subsystems implicated by the adverse events in Table 2.	FY09Q1 FY10Q4 FY11Q4	1.2.3.1, 1.2.3.2, 1.2.3.3, 1.3.3.1, 1.3.3.2, 1.3.3.3, 1.3.3.4, 1.3.3.5
Metrics	(i) Build modular, accelerated degradation platform for electronics, including capabilities for aging multiple types of power semiconductor components such as IGBTs and MOSFETs. Test platform shall allow for component aging induced from electrical and environmental acceleration factors including temperature cycling, electrical overstress, and temperature overstress. (FY09Q1) (ii) Using appropriate prognostic testbeds, demonstrate prediction of remaining useful life of aircraft components and systems pertaining to selected adverse events in Table 2 with quantification of prediction uncertainties using a mathematically rigorous assessment method. Prediction accuracy shall be within 25% at the integrated subsystem level of end of life when measured halfway between detectable onset of damage and end of life. Bounds of prediction uncertainty at the integrated subsystem level shall be reduced by 10% as measured from the initial prediction to the end of life. (FY10Q4) (iii) Using appropriate prognostic testbeds demonstrate prediction of remaining useful life of aircraft components and systems pertaining to selected adverse events in Table 2 with quantification of prediction uncertainties using a mathematically rigorous assessment methodology. Prediction accuracy shall be within 15% at the integrated subsystem level of end of life when measured halfway between detectable onset of damage and end of life. Bounds of prediction uncertainty at the integrated subsystem level shall be reduced by 30% as measured from the initial prediction to the end of life. (FY11Q4)		
Metric Rationale	A prediction of remaining useful life should be accurate and precise enough to lead to actionable decisions on the part of the targeted end users, whether it is automated systems, the crew, or maintenance workers. The metrics here are notional and will be updated depending on the systems analysis task, prognostic metric definition task, and the requirements of the chosen system. Several testbeds either already exist or are currently being built (i.e., a power semiconductor aging test platform, an EPS testbed, and an actuator test stand). The expected availability of the testbeds is factored into the timing of the milestones.		
2.1.4.1	Mitigation of flight computer and actuator failures and damage, and recovery from transient effects on flight computers with complex architectures, smart	FY09Q2 FY10Q4 FY11Q4	1.2.4.1, 1.3.4.1

	sensors, and actuators.		
Metrics	(i) Baseline performance of current commercial-grade avionics and actuators relative to recovery from transient effects (baseline activity will support metrics (ii) and (iii) below). (FY09Q2) (ii) Using commercial-grade avionics and actuators, demonstrate a minimum of 20% improvement over baseline established by Metric (i) in recovery time through the employment of new mitigation technologies. (FY10Q4) (iii) Demonstrate an improvement of 20% over baseline metric established in (i) via the SAFETI Lab and/or AirSTAR in aircraft loss of control prevention and recovery when failure/damage detection, diagnosis, prognosis, and mitigation is included in IRAC-developed flight control strategies. (FY11Q4)		
Metrics Rationale	A successful demonstration of measured improvement through the incorporation of flight computer mitigation technologies in flight control strategies will demonstrate practical application. The development of mitigation strategies for collateral damage and actuator faults and failures will provide a basis for further research. Flight computer systems must be robust to transient events and, for purposes of recovery and/or masking, there must be clear disambiguation of faults and failures resulting from environmental transients vs. those resulting from health management system design errors. This milestone will include demonstration of the ability to mitigate effects caused by ionizing radiation.		

IVHM 2.2 Airframe Health Management

Problem Statement: The goal of the Airframe Health Management element is to develop advanced technologies for airframe health management to enable effective detection, diagnosis, prognosis, and mitigation of damage in aircraft structures. Development activities at this level integrate the results of foundational research in active sensing and materials and in structural damage modeling for a comprehensive approach towards Airframe Health Management. As the use of composite materials in the construction of new aircraft continues to increase, emphasis on both metallic and composite materials and aircraft components is essential.

Research Approach: Airframe Health Management will validate and demonstrate methodologies and tools for integrated sensor technologies capable of detecting damage or degradation to airframe structural components. Based on the detection of damage or degradation, this element will perform in-flight diagnosis and assessment of the current state of health for the airframe. Using a continuous assessment of the health of the airframe this element will develop technologies to estimate the remaining useful life of airframe structural components and to mitigate further damage or degradation to the airframe through the in situ application of self-healing materials. This element will also demonstrate these capabilities through experimental validation methods in both a laboratory environment using appropriate testbeds and in actual flight conditions through the application of subscale flight testing.

The Airframe Health Management research area emphasizes the following two areas: Active Sensing and Materials, and Structural Damage Modeling. These areas include integration of new sensors and sensory materials, integration of new methods to provide accurate information to computational algorithms that reconstruct damage fields from sensor values, and integration of predictive algorithms to estimate structural durability and remaining life while the vehicle is in flight. In the area of damage mitigation, metallic and polymeric material with healing phases will be combined with detection, diagnostic, and prognostic methods to decrease the effects of damage and to improve safety. A key area of research in Airframe Health Management will be to study active sensing, i.e., the gains that can be made from building sensors that can also interact with their structural environment, thus moving the sensor from a purely passive, ‘data’ gathering mechanism to an active mechanism designed to obtain the best information for detection, diagnosis, prediction, and mitigation of adverse events.

The most credible and accurate analyses are generally those that have been validated using experimental data. Similarly, continuous in-flight correction of damage state predictions by integrating multi-modality sensor data will ensure the validity of the in-flight prognosis. In this integrated prognosis approach, inverse methods (to obtain current states) and forward methods (to predict the future behavior) will be combined with Probabilistic Risk Analysis (PRA) to account for uncertainties in measured and computed values to provide in-flight estimates of both the life of the airframe and the confidence in those predictions. Bayesian estimates, various statistical methods, and neuro-fuzzy methods will be considered for inclusion as part of the PRA.

IVHM 2.2 Airframe Health Management			
Number	**Title**	**Year**	**Dependencies**
2.2.1.1	Demonstrate the application of multiple complementary sensor technologies for detection of possible damage or degradation to airframe structural components.	FY10Q2	1.1.1.7, 1.1.1.8
Metrics	Demonstrate one or more technologies capable of detection of physical changes to airframe structural components that can accurately distinguish between damaged and undamaged component states to better than 80% area under the ROC curve using new sensor technologies with physics based models. Sensors must be complementary, and have the potential for enhanced detection when integrated. Technologies to be investigated include fiber optics, MEMS, and nano-technology		
Metric Rationale	Distinguishing between damaged and undamaged states to better than 80% area under the ROC curve supports the needs of the damage diagnosis methods and allows for greater accuracy to be assessed within the overall goals of the IVHM project.		
2.2.2.1	Validated methodologies and tools for the diagnosis of failures associated with airframe materials and structural components impacted by the adverse events in Table 2.	FY11Q2	4.4.4, 4.2.1, 1.2.2.1, 1.1.2.1, 1.2.2.4, 1.2.2.5
Metrics	Using appropriate diagnostic testbeds, demonstrate validated diagnosis of at least 3 of the 5 fault types (incipient, slow progression, fast progression, cascading, intermittent) using methods for modeling of damage processes and structural health monitoring techniques for diagnosis of incipient damage to greater than 80% area under ROC curve.		
Metric Rationale	Diagnostic algorithms must deal with a wide range of fault behavior; some techniques may deal with particular faults more effectively than others. The accuracy metric is notional and is based on the current state of the art. This accuracy metric will be adjusted based on the results of the systems analysis tasks.		
2.2.3.1	Validated tools and methodologies for the prognosis of structural failures in the Airframe.	FY10Q4 FY11Q4	4.4.4, 4.2.1, 1.2.2.1, 1.2.3.4

Metrics	(i) Demonstrate prognostic technologies capable of continuous assessment of the damage state to continuously improve uncertainty estimates of the remaining life of aircraft structural components by a factor of two over initial estimates at the time damage is first detected. (FY10Q4) (ii) Demonstrate application of computationally efficient predictive methods benchmarked on metallic Airframe structural components subjected to mechanical loads, with predictions of displacements, strains, and stresses to within 10% and predictions of failure quantities to within 15% of tested values. (FY11Q4)		
Metric Rationale	(i) Reducing the uncertainty of remaining life estimates by a factor of two enables the overall vehicle health to be assessed, for critical decisions and corrective actions to be made with greater confidence, and for the need for greater accuracy to be assessed within the overall goals of the IVHM project. (ii) It is expected that these predictions to the levels specified represent a reasonable compromise and will achieve the accuracy needed for damage estimation without being prohibitively computationally intense. The accuracy rates are based on current understanding of the overall needs for the IVHM project and will be reassessed based on the evolution of these needs and an assessment of changes to the state of the art.		
2.2.4.1	Demonstrate integrated self-healing material system concepts for in-situ mitigation of damage in structural elements subjected to representative loading.	FY09Q3 FY11Q2	1.1.4.1
Metrics	(i) Demonstrate an increase in critical flaw size by at least a factor of two for a metallic airframe structural component subjected to mechanical loads (FY09Q3) (ii) Demonstrate residual compression after impact strength of at least 60% of the undamaged compressive strength in a composite airframe structural component impacted at energies corresponding to catastrophic failure in a brittle epoxy composite material system. (FY11Q2)		
Metrics Rationale	These values represent a reasonable compromise between the increase in safety and the cost and complexity of achieving the desired self-healing properties.		
2.2.4.2	Joint IRAC / IVHM ground-based demonstration of structural fault injection, damage assessment, and degradation mitigation.	FY08Q4 FY09Q2 FY10Q2	1.2.2.4
Metrics	(i) Develop a ground-based experimental laboratory platform that can process at least 10 relevant parameters in real-time and integrate structural degradation monitoring technologies. (FY08Q4) (ii) Integrate IRAC-developed damage mitigating control with experimental laboratory platform in Metric (i). (FY09Q2) (iii) Establish a baseline for damage propagation for a specified flight profile and an associated metric for the damage propagation. (FY09Q2) (iv) Using the ground-experimental platform developed under Metric (i), demonstrate that, for a specified flight profile, damage propagation is reduced by TBD% compared to the baseline established in Metric (iii) when novel damage mitigating controls are engaged. The TBD% reduction will established jointly with IRAC and documented in the RTIP. (FY10Q2) * IRAC milestones related to success of this milestone: 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.2,		

	2.3.1.1, 2.3.1.2, 2.3.2.1, 1.2.7.1		
Metrics Rationale	The demonstration of damage mitigation capabilities in a laboratory environment enables ground testing of the mitigation technologies. The ground based studies and the percentage reduction of the structural damage will be set in this milestone.		
2.2.4.3	Joint IRAC / IVHM subscale flight demonstration of structural fault injection, damage assessment, and degradation mitigation to show ability to recover from potentially catastrophic failures.	FY08Q4 FY09Q2 FY10Q2 FY11Q2	1.2.2.4, 2.2.4.2, 2.2.4.4
Metrics	(i) Develop and demonstrate sub-scale fault injection experimental scenarios in conjunction with IVHM mitigation technologies to prevent, or recover from, at least two of the adverse events listed in Table 2. (FY08Q4) (ii) Complete validated software and hardware testbed for rapid deployment of advanced mitigation control law algorithms, telemetry of flight parameters and selected IVHM-specific sensors, and real-time execution of IVHM health assessment and mitigation algorithms (*collaboration with IRAC milestone 2.5.1.1). (FY09Q2) (iii) Design, develop, and instrument as appropriate, a subscale capability for flight testing novel damage-mitigating control technologies. (FY10Q2) (iv) Demonstrate on a subscale platform that the employment of damage-mitigating control strategies mitigates an otherwise catastrophic in-flight failure in response to injected structural faults. Document results in at least one peer-reviewed journal article. (FY11Q2) * IRAC milestones related to success of this milestone: 2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.2, 2.3.1.1, 2.3.1.2, 2.3.2.1, 1.2.7.1		
Metrics Rationale	Demonstrations of damage-mitigating control using both a lab environment and sub-scale flight testing provide a diverse environment for experimental assessment of airframe damage mitigation strategies. Interaction with IRAC-developed control software establishes validity and effectiveness of selected structural degradation technology for deriving health state parameters for reporting to load-alleviating control code.		
2.2.4.4	IVHM subscale flight data acquisition for detection, diagnosis, prognosis, and mitigation project elements as indicated in the RTIP for selected adverse events in Table 2.	FY08Q4 and Q4 of each subsequent year	4.4.4
Metrics	(i) Develop and demonstrate sub-scale fault injection experimental scenarios as indicated in the RTIP for IVHM detection, diagnosis, prognosis, and mitigation activities within 10% of the specifications set in the RTIP for the adverse event in question. (ii) Conduct subscale flight experiment and acquire least 20 sensor parameters sampled at 1 Hz for all phases of flight with signal-to-noise ratio greater than 1. (iii) Publish results of flight experiment on DASHlink along with at least 1 NASA Technical publication documenting the flight, data acquisition system, sampling rate, signal to noise ratio, special maneuvers, data dictionary, and an interpretation of the results. * Required IRAC collaboration includes resource scheduling, post-flight data reduction and packaging, flight profiles, and fault-injection scenarios.		
Metrics Rationale	This milestone is designed to provide the IVHM project with new data sets for analysis on a yearly basis with a sufficient number of sensors, sampling rate, and low signal to		

	noise ratio. The results will be made publicly available through DASHlink and will include appropriate documentation.

IVHM 2.3 Propulsion Health Management

Problem Statement: The goal of the Propulsion Health Management element is to develop advanced technologies to enable effective diagnosis and prognosis of engine performance and remaining life. Aircraft engines are highly complex systems consisting of static and rotating components, along with associated subsystems, controls, and accessories. 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. Over repeated flight cycles the life of many engine parts will degrade, and engine malfunctions may occur. Advances in Propulsion Health Management (HM) are needed to accurately monitor engine performance and assess remaining life.

Research Approach: The Propulsion Health Management element will focus on the development of new high-temperature sensors, energy harvesting methods, and communications techniques. Adaptive and robust detection of trends indicative of adverse engine performance will be tracked using model-based diagnostics to enable more accurate performance baselines to be established for individual engines, thus facilitating more accurate fault diagnosis. This area will also focus on the development of prognostic techniques to address localized effects and assess remaining useful life of rotating structures and other components and the generation of health state messages for use by the digital engine controller or maintenance crews.

IVHM 2.3 Propulsion Systems			
Number	**Title**	**Year**	**Dependencies**
2.3.1.1	Demonstrate high-temperature wireless sensing system for the detection of propulsion system anomalies.	FY9Q2, FY11Q2	1.1.1.3, 1.1.1.4,
Metrics	i) Breadboard demonstration of power scavenging at 300^{o}C with 3V voltage, pressure sensor at 300^{o}C, and a wireless circuit with RF communication at 300^{o}C over 1m distance. (FY09Q4) ii) Demonstrate an integrated self-powered wireless sensor system at 500^{o}C with data transmission over 1 m distance minimum and operational life of at least 1 hr. (FY11Q2)		
Metric Rationale	This is a realization of a complete stand-alone high-temperature wireless sensor system that relies on the integration of multiple sensing and support system elements, all operating at 500^{o}C. A wireless RF architecture will be developed to support data transfer requirements.		
2.3.1.2	Demonstrate multiple sensor technologies to enable detection in propulsion structural health monitoring systems.	FY10Q4	1.1.1.5, 1.1.1.11, 1.1.1.12
Metrics	Demonstrate stationary structural health using fiber optic technologies and rotating structural health using microwave sensor systems at 800°C and self diagnostic		

	accelerometer all in an operating engine environment.		
Metric Rationale	The combined sensor technologies will enable improved multiparameter detection of a range of relevant system operational conditions. For example, the combination of accelerometer data and precise knowledge of tip clearance can lead to an improved assessment of rotordynamic conditions and isolation of faults.		
2.3.1.3	Demonstrate multiple high-temperature sensors to enable improved gas path performance diagnostics.	FY11Q2	1.1.1.5, 1.1.1.6
Metrics	Demonstrate increased accuracy of fiber optic temperature probe, microwave tip clearance sensor and emissions sensor systems for operation at 600^{o}C and above in an operating engine environment.		
Metric Rationale	Increased accuracy of individual sensor measurements will lead to an increased estimation of unmeasured gas path parameters as determined by the gas path engine model. Correlation of the measured data and the gas path model will also allow for improvement of gas path model.		
2.3.2.1	Validated methodologies and tools for the diagnosis of faults associated with the propulsion gas path system implicated by the adverse events in Table 2. (i) Establish baseline gas path diagnostic system problem and metrics (FY08Q2) (ii) Apply sensor selection strategy to conduct two operating point sensor selection analysis (FY08Q4) (iii) Demonstrate a 10% improvement in estimation accuracy of integrated gas path sensing and diagnostics for aircraft engine health. (iv) Demonstrate integrated propulsion gas path sensing and diagnostics (FY10Q4)	FY08Q2 FY08Q4 FY10Q4	1.2.2.6, 1.2.2.7, 2.3.1.3
Metrics	Using appropriate diagnostic testbeds demonstrate validated diagnosis of Table 2 faults with an accuracy of 85% or more as measured by an appropriate ROC curve. (i)Consider at least 15 different fault types including of component, sensor and actuator faults. (ii)Quantify improvement over baseline sensor suite (iii) In simulation, quantify the improved estimation accuracy provide by advanced propulsion HM algorithms and sensors under NASA development. Demonstrate a 10% improvement in the estimation accuracy. (iv) In simulation, quantify the improved estimation and diagnostic performance provided by the advanced propulsion HM algorithms and sensors under NASA development. Demonstrate 10% improvement in estimation accuracy.		
Metric Rationale	Diagnostic algorithms are based on estimated quantities (propulsion thrust) in addition to measured parameters and are subject to both measurement uncertainties and estimation uncertainties. The accuracy metric is notional and will be assessed by the systems analysis tasks.		
2.3.3.1	Validated models and methodologies for the prognosis of high temperature static material failures in propulsion systems.	FY11Q4	1.2.3.5, 1.3.3.1, 1.3.3.2, 1.3.3.3, 1.3.3.4, 1.3.3.5
Metrics	Demonstrate a 15% enlargement in predictive horizon window over conventional non-unified methods for static structures at elevated (+500^{o}C) temperature given complex load		

	history involving overloads.
Metric Rationale	Implementation of this methodology to engine structural health management will result in significant enhancement of predictive capabilities based upon a fundamental understanding of structural and material properties

IVHM 2.4 Software Health Management

Problem Statement: The goal of the Software Health Management element is to develop the tools and techniques needed to enable the detection, diagnosis, prognosis, and mitigation of errors and related adverse events caused or contributed to by software systems in aircraft. While this bears many similarities to health management of physical systems, there are important differences that must be taken into consideration. The most important consideration is that all software faults are design errors. Software does not fail in the physical sense. However, aircraft software is inherently coupled with physical systems, and many faults in aircraft software are triggered by interactions with physical phenomena. Thus, software health can only be assessed in the context of the larger system in which the software is embedded. Unfortunately, there is little reliable data concerning software failure. Specifically (ref. 6, p. 39):

> *The lack of systematic reporting of significant software failures is a serious problem that hinders evaluation of the risks and costs of software failure and measurement of the effectiveness of new policies or interventions.*

This suggests an inherent difficulty in addressing detection and diagnosis of software faults. Furthermore, Avizienis, et al (ref. 7) observes that certain software faults are "recognized as faults only after […] a failure has ensued." It is possible that the first indication of a software fault is catastrophic system failure. A canonical example is the first flight failure of the Ariane 5 (ref. 14), which stemmed from sequence of seemingly reasonable design decisions. This highlights another observation of (ref. 6, p. 40) that "*by far the largest class of problems arises from errors made in the eliciting, recording, and analysis of requirements.*"

There are examples in the literature that can be considered software health management techniques. Sha (ref. 11) outlines an architectural mitigation strategy based on run-time monitors coupled with simple, safe, but otherwise sub-optimal alternative solutions. Goldberg (ref. 12) advocates adapting ARINC 653 Health Monitoring mechanisms to support monitoring of software using formal models of expected behavior. Castelli, et al (ref. 9) document a proactive approach to a class of aging software faults. In this context, aging refers to run-time degradation of software integrity due to resource exhaustion, data corruption, or accumulation of numerical errors. The strategy outlined is centered on periodically refreshing or restoring the state to eliminate the deleterious effects. This is a reasonable strategy for systems with long periods of continuous operation, and is worth considering for ground systems. However, for aircraft software systems, the flight duration is rarely more than ten hours. Airborne systems are already periodically restored to a known good state prior to every flight.

However, airborne systems may suffer from another form of software aging. Parnas (ref. 8) suggests two contributing factors for software aging: (1) not modifying software in response to evolving needs, and (2) modifying software in response to evolving needs. While there are mechanisms in place to manage changes to fielded software systems, this is an area with potential for either introducing new or unmasking existing software defects.

Research Approach: A central recommendation of the National Academies (ref. 6) is that dependable software systems should be developed with explicit claims and evidence to substantiate those claims, augmented with expertise in developing that class of systems. In light of these recommendations, research will be focused on developing a framework for (software) health management that involves:

- Explicit claims of system (and subsystem) requirements including assumptions about the application domain and environment in which the system is to operate;
- Evidence that software satisfies these explicit claims under the stated domain assumptions;
- Architectural principles, enforced by hardware mechanisms, that ensure that software behavior dependencies are traceable; and
- Mechanisms for correctly composing software systems from trusted components within the constraints imposed by the architectural principles.

To realize this framework, we propose exploring software health management in the context of system level dependability cases. Dependability cases are a mechanism recommended by Jackson (ref. 6) for managing the explicit claims and evidence in support of system dependability claims. The central idea behind this approach is that any observed (sub) system behavior that is inconsistent with any explicit (sub) claim in a dependability case is evidence that either the system or its associated dependability case is flawed. In either case, we have reason to doubt the dependability of the system. Initial tasks will focus on detection and mitigation techniques, with the anticipation that more robust detection capabilities will lay a foundation for future investigations into diagnosis and prognosis.

Another objective is to gain a better understanding of relevant software failure mechanisms for aircraft systems. There exist taxonomies of faults (refs. 7, 10). We will determine which classification scheme is appropriate for aircraft systems. Nikora (ref. 13) is currently analyzing historical software fault data (using the classification suggested in ref. 10) from several robotic space exploration missions. A similarly focused study of aircraft systems software failures is recommended.

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IVHM 2.4 Software Health Management			
Number	**Title**	**Year**	**Dependencies**
2.4.4.1	Evaluation of integrated adaptive reconfiguration of safety-critical aircraft software	FY12Q4	2.4.5.2, 2.4.5.3, 1.4.5.1, 1.4.5.2
Metrics	(i) Identify and document, via RTIP, a suitable experiment on a realistic testbed. Experiment documentation will include TBD evaluation metrics. Suitability of experiment/demonstration will be assessed in the context of HCSS peer review; experiment and metrics will show 100% traceability to these challenge problems. (ii) Demonstrate TBD performance (RTIP-specified) of adaptive reconfiguration of safety-critical aircraft software.		
Metrics Rationale	The study will include the identification of outstanding issues and an evaluation of potential impact on the deployment of these systems. The capability demonstration will provide confidence that the mitigation techniques are relevant to onboard IVHM systems.		
2.4.5.1	Initiate survey of state of the art assessment of software health management concepts and technologies (WAYPOINT)	FY08Q4	
Outcome	Findings will be collected in a document in a submission to a peer-reviewed conference.		
2.4.5.2	Framework for accumulating evidence that observed behavior, including both inputs and outputs, of a software system is consistent with its expected behavior.	FY09Q4 FY10Q2 FY11Q2	2.4.5.1
Metrics	(i) Perform a study to catalog historical aircraft software anomalies to include representative anomalies uncovered during pre-deployment verification and validation activities as well as those discovered post-deployment. From this catalog a set of working metrics will be derived for developing an evidence base. (FY09Q4) (ii) Instrument a relevant aircraft software / hardware instantiation to capture a minimum of two representative anomalies identified in the metrics established in (i). (FY10Q2) (iii) Collect data from an instrumented system and conduct a peer review of the framework with the multi-agency High Confidence Software (HCSS) coordinating group of the NITRD; document and report case study analysis results to an appropriate peer-reviewed journal. (FY11Q2)		

Metrics Rationale	The collected data will provide an evidence base that certain properties, especially certain extrinsic properties, are consistent with 1) explicit assumptions regarding system specifications and 2) explicit assumptions made with respect to certain physical devices with which the software interacts. Data will be provided to the Dashlink website for dissemination.		
2.4.5.3	Classification of software malfunctions for which 1) recovery is possible and 2) recovery is not possible. (WAYPOINT)	FY10Q4	2.4.5.1
Outcome	Delivery of a safety-critical software malfunction taxonomy that identifies classes of software malfunctions that are suitable to in-flight recovery by identifying sets of malfunctions for which software mitigation strategies are possible, and those for which it is not.		

Level 1 – Foundational Research

The following are statements of the problems and the solution approaches for the four elements of the Foundational level research at Level 1. IVHM 1.1 addresses Advanced Sensors and Materials, IVHM 1.2 addresses Modeling, IVHM 1.3 addresses Advanced Analytics and Complex Systems, and IVHM 1.4 addresses Verification and Validation. The Level 1 milestones are described for each of these four elements.

The foundational research in IVHM is to generate the fundamental tools and techniques to enable the automated detection, diagnostics, prognostics, and mitigation of adverse events during flight. To enable these capabilities, each Level 1 research element is further divided into subcategories, with ties to the project goal as shown in Figure 2.

IVHM 1.1 Advanced Sensors and Materials

Problem Statement: The goal of the Advanced Sensors and Materials area is to develop advanced sensors and materials that enable active and embedded sensing, sensing in icing and extreme environments, and self-healing materials. Sensing is an essential component to any IVHM system since sensor data is the foundation of any subsequent diagnosis and prognosis. The complete sensor system must be considered to be responsive to the overall need to reduce sensor size and weight, improve sensor reliability, and reduce sensor false alarm rate. New sensor technologies that not only passively sense their surroundings but also actively interrogate them are needed for the detection, location, and identification of damage.

Research Approach:
The approach taken in developing the sensor technologies will be to explore technologies including optical fiber-based sensing, micro-electromechanical systems (MEMS), and nanotechnology-based sensors. Sensing in extreme environments, ranging from situations produced by flight conditions (such as icing and lightning) to those produced by operation of the vehicle (such as high-temperature operation inside of an engine), is also necessary. Self-healing

materials are needed to respond to incipient damage states where access for manual repair is limited or impossible or where damage may not be detectable.

Active and Embedded Sensors

New sensor technologies will be developed to detect, locate, and identify damage by not only passively sensing their surroundings but also actively interrogating it as well. Promising sensor technologies include optical fiber-based sensing, micro-electromechanical systems (MEMS), and nanotechnology-based sensors. Emerging optical fiber-based systems may be embeddable into airframe structures, enabling thousands of sensors per fiber. Optical fiber-based sensors, including photonic crystal fibers and micro- and nana-structured fibers, can be developed to sense strain, vibration, acoustic waves, temperature, etc., and can be used in both passive and active interrogation modes. MEMS- and nanotechnology-based sensor systems could potentially serve as intelligent autonomous distributed sensor systems. They consume little power, are lightweight, and can operate in harsh environments. Carbon nanotube-based strain sensors may be embedded as part of a composite material system to provide three-dimensional strain mapping with high sensitivity and spatial resolution.

The approach in this work will be to consider the complete sensor system including the overall consistent need to reduce sensor size and weight, the need to improve sensor reliability, and the desire to reduce sensor false alarm rate. Advances in range of sensor system technologies provide opportunities for realizing remotely distributed and/or wireless sensor networks with self-powered or energy-harvesting capabilities. Energy harvesting will enable sensors to interrogate structures without extensive wiring to provide power. A communication infrastructure will allow data transfer within the distributed sensor network which will overcome the unique challenges of operation on a commercial aircraft.

Sensory metallic materials are structural metallic materials that contain a small percent by weight of either engineered second-phase “sensory” particles or nano-scale sensors. Because of their very small size and ubiquitous placement, the sensory particles allow detection of incipient damage and detection of damage in previously hard to inspect locations. These sensory microstructures must be designed so that the state of the particles accurately represents the state of the surrounding structural material. Emerging computational technologies such as discrete atomistic simulations and various continuum mechanics-based micromechanics analyses will be used for design of these materials. Additionally, advances in the processing and testing of both the mechanical and sensory response of prototype sensory microstructures are needed. Many of the fundamental damage analysis tools and experimental techniques required for the development of sensory metallic materials will be developed in collaboration with the Aircraft Aging and Durability project.

Sensing in Extreme Environments

To support IVHM throughout the aircraft, the ability to sense throughout the aircraft and in a range of vehicle conditions is necessary. Thus, sensing is necessary in extreme environments ranging from those produced by flight conditions, such as icing and lightning, to those produced by operation of the vehicle, such as high-temperature operation inside of an engine.

In addition to developing sensing mechanisms for icing conditions in propulsion systems, a critical first step in any health management process is the acquisition of physical system measurements via sensors. To develop sensors to detect icing conditions in the engine environment, this element will develop techniques for iced engine state awareness and hazard assessment based upon input from standard engine performance sensors and ice detection sensors on propulsion systems. This area of research would support part of FAA Safety Enhancement 139: "To prevent fatal accidents and incidents due to operations in hazardous icing conditions, research organizations, regulators, manufacturers, and operators should perform research to provide a means of accurate, reliable, and timely in-flight ice detection in all conditions."

State awareness is the foundation of diagnostics and prognostics, and present aircraft propulsion systems have limited self-awareness. New sensors systems, particularly in engine hot-sections, will be developed to increase the accuracy of predictive methods. Combined with the models and reasoners described below, the development of intelligent system hardware including sensors, processing electronics, communications, and power scavenging operable within engine hot-sections will provide fundamental technology that will be of use to developers of health management systems.

The integration of the system into an engine faces a range of technical challenges. A critical long-term need for IVHM is to develop high-temperature, low-weight, wireless, low-cost, durable sensors for a wide variety of applications including gas-path and structural temperature mapping; dynamic pressure, temperature, and strain sensors for the combustor, augmenters, turbine, and rotating components; chemical species for emissions and degradation; vibration and blade health sensors; and structural crack, damage, and load monitoring sensors. All of these sensors have a common need for enabling technologies which can be used to improve ease of application, reliability, and durability in engine environments. Thus there is a need to produce technologies which can enable smart sensor systems which can operate in harsh environments.

We have chosen to focus our high-temperature enabling technology efforts on developing high-temperature electronic circuits, wireless communications, and energy-harvesting technologies to enable the addition of high-temperature sensors into harsh environments while minimizing wiring and power requirements on the engine. In each of these areas we will be focusing on generating the fundamental knowledge required to give end users reliable access to this technology for incorporation into their own systems. The propulsion sensor development described above will be integrated as appropriate for demonstration purposes in this sub element.

Emphasis will be placed on understanding the fundamental physics of devices at temperatures of at least 500°C, a reachable goal which nonetheless demonstrates a fundamental revolution in the operation of high-temperature electronic devices. Passive electronic components for RF circuits will be developed, SiC device technology will be investigated for active electronic components, and energy harvesting will focus on developing thermo-electric-voltaic and photo-voltaic materials for generation of power for remote sensors.

Self-Healing Materials

Mitigation which restores load-bearing capability of a structure or the reduction in the rate of damage accumulation is significantly enabled when the mitigating mechanism is automatic and intrinsic to the vehicle. Mitigation involves either the restoration of some or all of the load-bearing capability of a structure under monotonic loading or the reduction in the rate of damage accumulation under cyclic loading. Materials that are capable of self-healing incipient damage states will be of great benefit in environments and conditions where access for manual repair is limited or impossible or where damage may not be detected. Structures made of either healing metallic or healing composite materials may have significantly prolonged service life and improved safety and reliability. New design and analysis methodologies will be developed to fully exploit the benefits of both types of healing material systems.

Healing metallic materials are structural metallic materials that incorporate a secondary healing phase or coating. The healing quality is the extent to which the initial mechanical properties of the metal can be restored or the degree to which fatigue damage can be suppressed. It depends not only on the mechanical properties of the healing material, such as strength and toughness, but also on the interface between the healing material and the structural material. Various candidate healing material-structural metallic material systems will be investigated to determine the optimum material combinations for both strength-critical and fatigue-critical conditions. Emerging computational, experimental, and processing technologies will be used to design and manufacture the materials for optimum damage mitigation.

Healing composite material systems rely on an appropriate combination of viscoelastic matrix properties so that the energy induced by the damage liquefies and flows through the matrix. While many advances have been made toward optimization of the fundamental properties of the matrix material, much work remains to develop corresponding composite material systems in which the self-healing capabilities of the matrix suppress delamination and matrix cracking. Research will be conducted on the development of cost-effective processing methods for mass production of self-healing matrix materials, optimization of the matrix-fiber interface properties, optimization of processing methods to make the self-healing matrices amenable to integration into a functional composite system, and characterization of the properties of the new material systems.

IVHM 1.1 Advanced Sensors and Materials			
Number	**Title**	**Year**	**Dependencies**
1.1.1.1	Mapping of the advanced sensors and materials metrics (quantitative and qualitative) to potential user requirements.	FY09Q2 and each year thereafter	4.2.1, 4.2.2, 4.2.3
Outcome	Document, updated annually, that shows relationship between milestone metrics and user requirements.		
1.1.1.2	Demonstrate ice crystal sensing in high density icing environment for engine icing applications.	FY11Q2	1.1.1.1
Metrics	Demonstrate real-time state assessment methods with sufficient time response to alert crews within 3 minutes of an impending ice crystal hazardous encounter as demonstrated in the NASA Ice Contamination Affects Flight Training Device.		
Metric Rationale	Implementation of instrumentation and sensors to determine the icing conditions to which an engine is exposed and the influence of the ice contamination upon the engine operations. Optimal sensor placement is TBD at this time.		

1.1.1.3	Demonstrate power harvesting at high temperatures to enable remote sensing technologies.	FY09Q4	1.1.1.1
Metrics	i) Demonstrate uni-couple thin film Thermoelectrics (TE) at 500°C in oxidizing environment for >10 hours at level of 300 mW.		
Metric Rationale	Stand-alone wireless systems operating at high temperatures require power supplies that can provide adequate power for operation at a temperature of 500°C. These systems do not presently exist. This milestone shows a benchmark of thin film thermoelectrics from proof of concept to viable operation at voltages relevant to powering of microsystems. The present estimate of the power requirement for wireless communication is less than 500 mW. This milestone is a stepping stone towards higher power (1W) systems with an ambient heat sink.		
1.1.1.4	Demonstrate wireless sensor system elements.	FY10Q4	1.1.1.1
Metrics	Demonstrate RF sensor data signal transmission over a distance of 1 m operating at 500^{o}C for at least 1 hour, and a sensor readout rate of 100 Hz, with circuit, including RF transistor, antenna, and sensor, integrated onto a single package.		
Metric Rationale	High-temperature RF data transmission requires integration and operation of multiple components including an RF transistor, as well as components such as antennas, resistors, and capacitors. This metric demonstrates basic RF wireless transmission technology of sensor data at record temperatures.		
1.1.1.5	Demonstrate optical propulsion health management fundamental technologies	FY10Q3	1.1.1.1
Metrics	i) Demonstrate embedded or surface mount optical fiber technologies for strain measurements with a sensitivity of 10 microstrain. ii) Dynamic temperature sensor capable of 1000^{o}C operation with less than +/-20^{o}C error within 1000 hour lifetime.		
Metric Rationale	The fundamental operation of high-temperature fiber-optic technology needs to be demonstrated for it to be implemented in integrated systems. This metric demonstrates strain, temperature, and communication technologies at new limits of durability and temperature.		
1.1.1.6	Demonstrate health monitoring nanostructured sensors for the monitoring of propulsion emissions.	FY09Q4	1.1.1.1
Metrics	Demonstrate nanostructured oxide sensors integrated in microsensor platforms with an operating temperature up to 600^{o}C and operable over 50 hours measuring hydrocarbons at a level of 250 ppm.		
Metric Rationale	The monitoring of propulsion emissions is a valuable tool for the detection of system wide propulsion system degradation. Nanostructured oxides are the next generation of sensing materials but their fabrication into sensing structures is a significant challenge. This milestone is a benchmark toward the use of nanostructured oxides in emission sensing applications.		
1.1.1.7	Demonstrate structural sensors to provide intelligent or smart sensing capabilities.	FY09Q4	1.1.1.1
Metrics	Examine all of the following concepts and eliminate any that do not show potential for meeting stated metrics: i) High-density multi-functional fiber-optic based sensor array capable of better than 10% FSR µstrain and temperature resolution. ii) MEMS smart sensor capable of better than 10% FSR µstrain resolution.		

	iii) Single wall carbon nanotube sensor array for multi-axis strain mapping accurate to within 10%. iv) Fiber rosette strain measurement to within 5% of the benchmark foil strain gage measurements. v) Real-time Bragg Grating demodulation technology to measure the strain of 3-core fiber to with 90% accuracy.		
Metric Rationale	To develop a robust IVHM sensing capability, optimal baseline accuracies need to be established. These accuracies will be determined in this milestone. These accuracy metrics are based on a realistic assessment of the current state of the art and on current airframe structural health sensing needs for damage detection. Further refinements to these accuracy estimates will be addressed by this milestone.		
1.1.1.8	Demonstrate validated physics-based models of sensor performance.	FY08Q2, FY08Q4, FY09Q2	1.1.1.1
Metrics	Demonstrate modeling for the following and document findings in an appropriate NASA Technical Publication for the following physics-based models: (i) Develop and document physical models of Bragg wavelength shifts for fiber optic sensors with 90% modeling accuracy as compared to the experimental data for SHM applications. (FY08Q2) (ii) Develop and document Fourier optics modeling of fiber optic sensors for structural health monitoring with 90% modeling accuracy as compared to the experimental data. (FY08Q4) (iii) Develop and document transfer matrix modeling of fiber optic sensors for structural health monitoring with 95% modeling accuracy as compared to the experimental data. (FY09Q2) (iv) Develop and document first order multi-physics models of MEMS based sensor incorporating electrical, mechanical, and acoustical domain behavior with 90% modeling accuracy, as compared to the experimental data, using first order effects only. (FY08Q4) (v) Develop and document second order multi-physics models of MEMS based sensor incorporating electrical, mechanical, and acoustical domain behavior, with 95% modeling accuracy, as compared to the experimental data, using both first and second order effects combined. (FY09Q2) (vi) Develop and document SOA assessment of current physics based models of nanoscale sensors for SHM applications. (FY09Q2)		
Metric Rationale	Accurate models will reduce the uncertainty associated with prototyping process and thereby reduce the number of prototypes that require fabrication. This will decrease costs while delivering devices that meet the IVHM sensing needs. The models will also give a better understanding of the sensing mechanism and how it can be exploited to create better sensors.		
1.1.1.9	Demonstrate current detection sensor capable of sensing lightning strikes which could potentially present hazards to avionics on composite-based aircraft.	FY10Q2	1.1.1.1
Metrics	i) Detect lightning and High-Intensity Radiated Field (HIRF) events to within 6 dB peak intensity within a 50 microsecond time window.		

	ii) Document lightning current detection capabilities via an exploratory paper on direct lightning current measurements.		
Metric Rationale	6 dB accuracy will allow distinction between DO-160 waveforms A and D. A 50 microsecond detection threshold will allow resolution between multiple burst and multiple stroke induced transients.		
1.1.1.10	Flight speed capable Isokinetic Total Water Content Probe.	FY10Q3	1.1.1.1
Metrics	Demonstrate the ability to measure total water content up to 2 g/m^3 using Isokinetic Total Water Content Probe at 200 m/s true airspeed which is only geared towards lower speed take off and approach conditions.		
Metric Rationale	200 m/s is the target airspeed for convection generated ice cloud penetration with research aircraft. This speed is beyond the current probe's capability.		
1.1.1.11	Demonstrate microwave sensor system's ability to make blade health measurements demonstrated on a rotating blade.	FY09Q4	1.1.1.1
Metrics	Demonstrate microwave sensor capable of measuring blade inclination +/- 5 degrees and tip clearance of 100 microns in an ambient temperature of 150 C.		
Metric Rationale	Blade inclination or elongations are indicators of blade structural health. The microwave sensors will be located in the engine casing and the temperature range for these initial measurements will be slightly above ambient temperatures.		
1.1.1.12	Demonstrate Self Diagnostic Accelerometer in a typical engine operating environment	FY10Q2	1.1.1.1
Metrics	Demonstrate the capability to diagnose sensor structural or electrical damage, temperature changes, and also sensor loosening by a ¼ turn.		
Metric Rationale	Sensor failure can be caused by structural damage or electrical damage of the sensor and also the loosening of the sensor attachment to the engine. The sensor will continue to function properly until it has loosened by ½ turn.		
1.1.2.1	Characterize the effects of lightning and high intensity radiated fields to avionics systems on composite-based aircraft for 100% of the HIRF test requirements documented in DO160 Section 20.6 & 22.	FY10Q4	1.1.1.1
Metrics	Measure Lightning Induced Transient Susceptibility and Radio Frequency Susceptibility by using RF reverberation chamber mode-tuning, probe calibration, lightning waveforms, and current measurement techniques as specified in RTCA/DO-160F Sections 20 and 22. Use the methods to successfully measure frequency and power susceptibility levels, acquire data, and characterize the effects of lightning and HIRF on avionic systems/components located near/on composites or in fault-tolerant architectures. RF Susceptibility level capabilities shall meet Category L (up to 490 V/m CW from 2 to 4 GHz and 7200 V/m Peak from 4 to 6 GHz). Lightning Transient cable bundle single stroke, multiple stroke, and multiple burst test capabilities shall meet Test Level 4 (up to 1500V and 2000A for Single Stroke waveforms).		
Metric Rationale	Up-to-date laboratory capability is needed for credible verification and validation of diagnostic and prognostic algorithms used in new fault-tolerant avionics architectures and for measurement of lightning/HIRF effects.		
1.1.4.1	Engineered materials for structural health	FY09Q2,	1.1.1.1

	management and mitigation of structural damage.	FY09Q4, FY10Q2	
Metrics	i) Demonstrate a reduction in crack driving force by at least a factor of two compared with baseline titanium and aluminum alloys. (FY09Q2) ii) Develop an in-situ method for testing engineered material systems for direct measurement of displacement within 0.1 microns across interfaces of engineered materials and structural materials to facilitate accurate local strain measurements. (FY09Q4) iii) Develop molecular dynamics, multiscale or micromechanics methods for predicting load transfer characteristics within 20% of measured across the interfaces between engineered materials and structural materials. These methods are being developed in conjunction with damage science methods under development in Aircraft Aging and Durability. (FY10Q2) iv) Demonstrate a scalable processing method for the production of self-healing composite matrix materials by fabricating increasingly larger test articles: 3x3 in^2, 6x6 in^2, 12x12 in^2. Baseline the volume of production of self-healing composite matrix materials to within 5% (FY10Q2) v) Down select technologies based on success of achieving above metrics. (FY10Q2)		
Metrics Rationale	(i) Reduced crack driving force factor is sufficient to demonstrate concept and provide baseline for refinements based on continued development of healing agents. (ii) Necessary for experimental validation of models and determine the fundamental physical damage processes. (iii) Each of these methods is at the forefront of modeling damage processes in structural materials and will contribute to development of the engineered material systems. (iv) Necessary to produce sufficient quantities of polymer required: (1) to advance technology maturation. (2) to demonstrate a self-healing polymer matrix for a more damage tolerant structural composite. (v) Pursue technologies that appear best suited for the continued development of engineered materials and engineered material systems. ** This milestone is being worked collaboratively with AAD milestones 1.2.03, 1.2.07, and one new milestone (still unnumbered) for incorporation of multiscale constitutive relationship into a 3D microstructural model.		

IVHM 1.2 Modeling

Problem Statement:

The goal of the Modeling element is to develop the physics-based modeling capabilities critical to validated detection and prognostic methods for adverse events during flight. Model based detection and prognosis algorithms inherently incorporate estimates of uncertainty within generated estimates. These uncertainty estimates are critical to enabling exploration of the trade-space between necessitating immediate action and utility to the operator in terms of confidence in a correct response. Computational efficiency of these physics based models (and correspondingly the appropriate level of fidelity) is necessary to be applicable in the resource constrained environments of flight. This element relies on advanced physical models of the propagation of known failures through materials, propulsion systems, and aircraft systems in order to provide an assessment of the remaining useful life (RUL) of applicable items listed in Table 2.

Research Approach:
We will research and develop techniques in Bayesian Modeling, Structural Damage Modeling, Damage Characterization and Propagation, Estimating Remaining Useful Life, and Design Tools in support of research area milestones at Levels 2, 3 and 4. The research will develop methods for detection and prediction, examine the representation and management of uncertainties in such estimates, and establish physics based models for various aircraft systems (e.g. damage propagation). A rigorous mathematical framework will be employed to characterize the predictions and the confidences in those predictions using relevant metrics.

Bayesian Modeling Techniques
An important mathematical foundation for the IVHM project is Bayesian probability theory, which allows for the explicit modeling of uncertainty due to measurement noise as well as modeling error. A key area of work is to develop model-based methods that enable detection, diagnosis, and prognosis. Bayesian modeling as applied to aeronautic sub-systems consists of two fundamental areas: i) how to probabilistically model the behavior of the physical system under study, and ii) how to perform inferences using the model to infer the condition (i.e. state of health). This effort will develop tools that allow for flexible model specification (e.g. as Booleans, state diagrams, ordinary differential equations) and provide an inference engine that can search over the large space of possible causes of the given observations so as to provide the most probable diagnoses (fault conditions) within a practical time-frame.

Probabilistic techniques that characterize and understand damage propagation and form estimates of remaining useful life are needed. The models incorporate our understanding of system physics along with prior information (e.g. appropriate value ranges of variables) within a rigorous mathematical framework designed to automate parameter retrieval. The retrieval process, also known as inversion, inherently incorporates estimates of uncertainty associated with each of the retrieved parameters. This notion of uncertainty is critical when making tradeoffs associated with minimizing false positives and also when maximizing accuracy of future fault progressions. The successful application of the Modeling element executes research into hybrid (discrete and continuous variables) reasoning, time-varying (non-stationary, non-Markovian systems), and Bayesian change detection methods, for example.

Structural Damage Modeling
Computationally efficient algorithms will be developed suitable for use in flight, including development of techniques to enhance the accuracy of predictive algorithms through integration of multi-modality sensor data. Predictive methods suitable for estimating damage growth and residual life of structural components during flight and in the presence of multiple arbitrary damage sites require both accuracy and unprecedented computational efficiency. Among the candidates that will be developed for satisfying these simultaneous requirements are the Extended Finite Element Method (X-FEM) and the response surface method based on prior rigorous solutions. X-FEM is a new and promising formulation that implements a discontinuous function combined with asymptotic crack-tip displacement fields to enable the domain to be modeled by finite elements without explicitly meshing the crack surfaces. Thus, the location of

the crack discontinuity can be arbitrary with respect to the underlying finite element mesh and quasi-static or fatigue crack propagation simulations can be performed without the need to re-mesh as the crack advances. Less elegant, but more well established, than the X-FEM, a predictive methodology based on response surfaces tuned to represent computationally intensive finite element solutions will allow very rapid interrogation of the damage state. Since the response surfaces can address only cases that have been previously considered via detailed analyses, the specific parameter space for their construction must be considered very carefully. This work is being conducted in partnership with the Aircraft Aging and Durability Project.

Damage Characterization and Propagation

Diagnostic tools for monitoring and interpreting sensor data for the initiation and propagation of structural damage are an integral part of an IVHM system. Predictive methods suitable for estimating damage growth and residual life of structural components during flight and in the presence of multiple arbitrary damage sites require both accuracy and unprecedented computational efficiency. New developments will include new techniques that facilitate processing of sensor data, and may incorporate optical frequency-domain reflectometry (OFDR) into fiber-based diagnostic systems and an electrical impedance damage detection (EIDD) method that uses neural networks to obtain an inverse solution based on electrical conductivity mapping.

Techniques will be developed to facilitate demodulation, processing, and integration of advanced sensor suites. Additionally, new algorithms for diagnosis of structural health using sensors in surface and embedded distributions will be developed. The accuracy, dynamic range, and reliability of existing fiber optic-based structural shape sensing technology will be evaluated, and a computationally efficient fiber Bragg grating interrogation technique will be integrated into existing OFDR technology for high-speed structural shape sensing.

Two types of inverse methods will be developed to diagnose damage in the structure. EIDD is based on electrical conductivity mapping and inverse methods, and has shown promise as an alternative approach to diagnosing the state of internal damage. EIDD is a methodology rooted in medical imaging techniques, whereby in-situ electrical resistance measurements of a conductive or partially conductive material are input to an artificial neural network or other inverse algorithm that has been trained *a priori*, based on finite element models of electrical resistance using heat transfer models. The computed inverse solution allows both the location and magnitude of structural damage to be quantitatively estimated from these resistance measurements in near real time.

Estimating Remaining Useful Life

As subsystems (e.g. electrical actuators) age, their performance may degrade in a non-linear manner such that some acceptable loss in performance slowly occurs, but some time later progresses to a possibly sudden change with unacceptable consequences. Without a reliable means to assess degradation progress and therefore to estimate remaining useful life, subsystems that begin to show signs of degraded performance are replaced earlier than necessary. The results are unscheduled down-time as well as a higher than necessary fleet maintenance cost.

This effort will establish model-based methods that accurately predict the time to failure of physical sub-systems. The remaining useful life estimate can then be used to assess when maintenance can be delayed and to optimize part replacement. Concepts will be developed for identifying degradation trends and/or anomalous conditions using physics-based, data-driven, and statistical approaches. Bayesian sensor fusion tools will be designed and developed for robust state estimation as well as to distinguish false sensor failures from true failures. An actuator testbed will be used to detect performance degradation and to develop models for estimating the remaining life of actuators.

Design Tools

We will develop algorithms and methods that treat the IVHM system design process as a multi-criteria, multi-disciplinary optimization problem. Existing work includes modeling components as functions and figuring out the best way to combine these to perform more complicated tasks, as well as conducting cost-benefit analyses of IVHM sensors. The benefits include the reduced probability and severity of incidents and accidents because of the additional information that the sensor provides and the costs include any unnecessary maintenance actions that result from false positive indications. However, there are more considerations in designing IVHM systems. For example, when deciding whether to add a sensor, one has to consider how ambient conditions in the area where the sensor will be mounted may affect its accuracy. We will incorporate the metrics of IVHM technologies that we obtain from systems analysis. This will enable the incorporation of additional relevant constraints and optimization metrics. This increasing automation of the design process gains importance as the number of IVHM components, constraints, and figures of merit increases.

We plan to coordinate with the projects within the Fundamental Aeronautics Program (specifically the MDAO IDG) to incorporate the design of IVHM systems into the aircraft design process. The goal is to move beyond the current practice of designing IVHM systems as an afterthought after the aircraft is designed and manufactured, and instead enable the design of the IVHM system as part of the aircraft design process.

IVHM 1.2 Modeling			
Number	**Title**	**Year**	**Dependencies**
1.2.2.1	Mapping of the modeling metrics (quantitative and qualitative) to potential user requirements.	FY09Q2 and each year thereafter	4.2.1, 4.2.2, 4.2.3
Outcome	Document, updated annually, that shows relationship between milestone metrics and user requirements.		
1.2.2.2	Develop Bayesian methods and hybrid reasoning techniques for robust state estimation and diagnosis of abrupt, continuous, intermittent, and cascading faults.	FY08Q4 FY09Q4 FY10Q4	3.2.1, 1.2.2.1, 1.2.2.3
Metrics	i) Develop and evaluate Bayesian models that diagnose an unbounded (i.e. bounded only by the number of health variables, not by a fixed constant) number of multiple discrete faults, including sensor faults, component faults, and sensor plus component faults. Faults may take place simultaneously or sequentially. Evaluate using experimental multiple-		

	fault data in the ADAPT testbed (FY08Q4). ii) Investigate the modeling of at least three faults types such as continuous, intermittent (transient), cascading, and/or dynamic faults, using Bayesian networks. The selection of the fault types will be informed by the Adverse Events Table as well as the capabilities of the testbed in which the novel approach will be validated. Demonstrate, in experiments, better than 85% accuracy for diagnosing the selected fault types. (FY09Q4). iii) Develop Bayesian methods and/or models for varying operating conditions and demonstrate fault detection/diagnosis on at least three faults types such as discrete, continuous, abrupt, transient, or cascading faults. Examine tradeoff between accuracy and diagnosis time. Demonstrate, in experiments, better than 95% accuracy for diagnosing faults in sub-scale experiments in real-time (FY10Q4). iv) Improve the memory and timing performance of hybrid reasoning tool HyDE (Hybrid Diagnosis Engine) on scenarios from the ADAPT testbed by a factor of 50%. Improve the predictability by providing capabilities to restrict time and memory usage of HyDE at single reasoning step; provide quantitative estimates on time and memory usage of HyDE to guarantee that they do not increase monotonically. (FY08Q4) v) Integrate capabilities for stochastic reasoning (specifically Bayesian Networks) to support reasoning under uncertainty. Demonstrate effectiveness of this approach on ADAPT testbed for scenarios that consist of data with 2%-5% noise added. (FY09Q4) vi) Develop modeling paradigm and supporting reasoning technologies to diagnose multiple classes of faults listed in the Adverse Events Table. Demonstrate the application of these models and technologies for diagnosis of representative faults on a sub-scale testbed with less than 1% false positive rate (per flight) while improving false negative rate by 25% over baseline performance as determined in 3.2.1. (FY10Q4)		
Metric Rationale	Many existing fault isolation and diagnosis techniques only handle a fixed number of faults, typically one fault. It is important to go beyond this, and also to improve the understanding (by experimentation) of what happens as the number of faults increases. ii) There is a need to improve the physical understanding, simulation capabilities, and diagnosis techniques in several areas. By carefully exploring different candidate fault types and their propagation mechanisms and fault signatures, their importance in applications, as well the scientific and technical feasibility of modeling them, we will pick the three most promising fault types. iii) Execution time must be fast and predictable such that mitigation actions can be taken quickly. Accuracy levels are aggressive but achievable. iv) Onboard execution of hybrid reasoning algorithms requires improvements in time and memory usage to fit within computational resource constraints. v) Diagnostic solutions have to be robust in the presence of noise in data from sensors to reduce the false positive and false negative rates as a result of ambiguity based on the noisy data. vi) Metrics are estimated based on preliminary experiments. Rates will depend on fault type and the nature of the system which is used.		
1.2.2.3	Develop metrics for comparing and assessing different diagnostic methods on testbed failure scenarios.	FY09Q2	1.2.2.1
Metrics	i) Develop fault catalogue that captures different fault classes and properties as exemplified by the Adverse Events Table.		

	ii) Develop a set of metrics that would assess the technical performance of different diagnostic algorithms. iii) Develop the data generation and metric evaluation process for benchmarking diagnosis systems. iv) Demonstrate the benchmarking capability on at least one diagnosis algorithm for at least 5 metrics.		
Metric Rationale	To validate diagnostic technologies, a consistent methodology for classifying diagnostic problems and for evaluating the technical performance of different diagnostic technologies must be established.		
1.2.2.4	Develop computationally efficient algorithms for in-flight diagnosis and characterization of damage to metallic and composite aircraft structures.	FY10Q4	1.2.2.1
Metrics	Demonstrate deterministic methods for diagnosing the location and size of the damaged region within 85% of its actual location and size, and disambiguation of the type of adverse event shown in Table 2 within 80% accuracy.		
Metric Rationale	Accuracy is directly related to the computational efficiency of the modeling methods and represents a reasonable compromise to achieve the accuracy necessary for real-time diagnosis without becoming too computationally inefficient to be practical for in-flight operation. Accuracy will be tied to user requirements specified in 1.2.2.1. This milestone is being worked collaboratively with AAD milestone 1.5.04.		
1.2.2.5	Develop diagnostic methods for analysis of damage processes using molecular dynamics, multiscale, and micromechanical modeling methods and in-situ evaluation methods for diagnosing damage in IVHM material systems.	FY10Q4	1.2.2.1
Metrics	Demonstrate ability to diagnose modes of damage that are within 80% of observed experimental validation results.		
Metric Rationale	This is a new technique, so the current level of agreement is 0%. Correlation inaccuracies are based on the current state of the art modeling methods. The stated tolerance is aggressive but achievable.		
1.2.2.6	Develop and demonstrate propulsion gas-path performance deterioration trending.	FY10Q4	1.2.2.1
Metrics	In simulation, demonstrate on-board propulsion performance deterioration trending with < 2% average estimation error.		
Metric Rationale	Individual component performance losses are currently as high as 10% (see NASA-CR-135448). Estimation approaches which provide < 2% estimation error will enable significantly enhanced diagnostic detection and isolation capabilities.		
1.2.2.7	Develop and demonstrate propulsion thrust estimation techniques.	FY10Q4	1.2.2.1
Metrics	Demonstrate thrust estimation techniques to detect thrust asymmetry conditions > 10% absolute thrust, within 20% relative accuracy.		
Metric Rationale	Estimation approaches which provide 20% or higher relative accuracy will enable significantly enhanced thrust estimation capabilities.		
1.2.3.1	Validated prognostic and life estimation models for electromechanical actuators.	FY09Q2 FY09Q4 FY10Q4	1.2.2.1, 1.2.3.2, 1.2.3.6, 1.2.3.7

Metrics	(i) Show fit of actuator model to historical data, experimental data, or simulated data to be within 10% RMS error. (FY09Q2) (ii) Show fit of health assessment module for selected fault modes on an actuator components to be within 10% RMS error. (FY09Q4) iii) Demonstrate actuator prognostic models under at least 3 different load conditions. Prediction accuracy shall be within 10% of end of life when measured halfway between detectable onset of damage and end of life. (FY10Q4)		
Metric Rationale	Once damage has been detected, a prediction of end of life is made and refined as additional data is applied. Given a known end of life measure for a particular component, the prediction of the prognostic models should be within 10% of that end of life measure when using limited time duration of the data after onset of damage. Different components will have different damage propagation times. 10% accuracy is perceived to be aggressive but achievable based on the literature.		
1.2.3.2	Develop and evaluate data-driven, physics-based and hybrid prognostic models and methodologies in centralized and distributed implementation schemes.	FY08Q4 FY09Q4 FY10Q2 FY10Q4 FY11Q4	1.2.2.1, 1.2.3.6, 1.2.3.7, 3.3.1, 3.3.3
Metrics	i) Develop and benchmark data-driven, model-based and hybrid prognostic algorithms to achieve 10% improvement over baseline standards set in task 3.3.1 and 3.3.3. (FY10Q2). ii) Implement the prognostic algorithms developed on a distributed platform to achieve real-time performance at 0.1 Hz sampling rate. (FY09Q4) iii) Make 36 run-to-failure degradation datasets ranging over different operational and environmental conditions available to the research community-- 4 in FY08Q4, 16 in FY09Q4 and 16 in FY10Q4. iv) Make available for download a software tool to evaluate prognostic algorithms over different metrics (from 3.3.2) and published datasets. (FY09Q4) v) Develop and benchmark distributed prognostic algorithms to achieve 50% execution speed improvement over centralized algorithms. (FY10Q4) vi) Conduct comparative analysis of different prognostic algorithms with recommendations for application. (FY11Q4)		
Metric Rationale	Setting up a testbed or simulation to simultaneously generate degradation data as well as develop and evaluate prognostics techniques, with corresponding publications, will greatly aid in setting standards in the field of prognostics and improving system safety. The performance improvement objectives for the different algorithm development stages are aggressive but realistic goals given the absence of standardized prognostics metrics in contemporary scientific literature.		
1.2.3.3	Validated prognostic and life estimation models for electronics.	FY09Q1 FY10Q4 FY11Q2	1.2.2.1, 1.2.3.2, 1.2.3.6, 1.2.3.7
Metrics	i) Secure arrangements for post-mortem analysis to understand and characterize aging mechanisms. (FY09Q1) ii) Develop physics-of-failure, data-driven, and hybrid models for estimating remaining useful life of at least three electronic component failure mechanisms. (FY10Q4) iii) Demonstrate electronics prognostic models under at least 3 different operating conditions (temperature, electrical stress, etc.). Prediction accuracy shall be within 10% of		

	end of life when measured halfway between detectable onset of damage and end of life. (FY11Q2)		
Metric Rationale	Once damage has been detected, a prediction of end of life is made and refined as additional data is applied. Given a known end of life measure for a particular component, the prediction of the prognostic models should be within 10% of that end of life measure when using limited time duration of the data after onset of damage. Different components will have different damage propagation times. Metrics were chosen based on what are perceived to be aggressive but achievable goals based on the literature.		
1.2.3.4	Prognostic airframe structural model for near real-time estimation of damage propagation.	FY08Q4 FY09Q4	1.2.2.1, 1.2.3.6, 1.2.3.7
Metrics	i) Develop initial simulation of airframe prognosis that is conditioned on airframe structural load and environments. Model prediction output deviation shall be within 25% using historical data. (FY08Q4) ii) Develop a computationally efficient prognostic model incorporating diagnostic information. Prediction accuracy shall be within 20% of end of life when measured halfway between detectable onset of damage and end of life. (FY09Q4)		
Metric Rationale	To develop a robust IVHM damage prognostic capability, the levels of fidelity of the models need to be established. These levels will be based on 1.2.2.1.		
1.2.3.5	Coupled deformation and damage methodology for propulsion structural materials.	FY08Q4 FY09Q4 FY10Q4	4.2.1, 1.2.2.1, 1.2.3.6, 1.2.3.7
Metrics	i) Develop report describing experimental program and data content required to appropriately characterize a GVIPS (generalized viscoelastoplastic with potential structure) class deformation and damage model (FY08Q4) ii) Demonstrate GVIPS-class deformation and damage prediction using finite element-based model simulations that are accurate to within 5% under idealized uniaxial conditions (FY09Q4). iii) Demonstrate GVIPS-class deformation and damage prediction using finite element-based model simulations that are accurate to within 5% under biaxial conditions (FY10Q4)		
Metric Rationale	i) In order to properly characterize and apply the GVIPS-class models, the required data content must be obtained. The developed document will quantify the required testing required for the IVHM program, as well as provide guidance to future researchers on the types of experiments and data content that are required in order to properly characterize the model. ii) To identify appropriate local and global failure criteria, viable models are necessary. This metric demonstrates that the methodology can capture the interactive effects of complex load histories (e.g., overloads, cyclic, thermomechanical, etc.), geometric imperfections, and structural stress risers on the deformation and life response. iii) This metric demonstrates that the developed methodology can also capture the interactive effects of multiaxial stress states along with complex load histories on the deformation and life response.		
1.2.3.6	Performance evaluation methods for prognostic systems.	FY09Q4	1.2.2.1
Outcome	i) Compile and consolidate performance assessment methods for current and potential prognostic applications and extract requirement criteria for declaring a prognostic scheme		

	successful in each application aspect (e.g. based on time horizons, criticality, targeted end user of prognostic information). Produce peer-reviewed conference and journal articles to gain consensus in the research community on prognostics definitions and standards. Depending on partnership possibilities the scope of further work will be defined. (FY09Q1 WAYPOINT 1) ii) Based on shortcomings identified in i) and in collaboration with academia and/or industry define new prognostic metrics and apply them to the various test applications in proof-of-concept demonstrations using testbed and simulation data. Produce publications enumerating various new metrics identified for prognostics and their application significance in various applications. Depending on the availability of newer applications these metrics may need modifications or new metrics may be required. (FY09Q3 WAYPOINT 2)		
Metric Rationale	There is significant disagreement on prognostics definitions and evaluation metrics. Requirements are different for different applications and hence a common consensus on evaluation standards has not been reached. A comprehensive review and classification of such applications will help set standardized procedures among the community. This will help define validation standards for prognostics technologies to aid in their fielded applications.		
1.2.3.7	Validated methodologies for prognostics uncertainty management and representation.	FY09Q3, FY11Q4	1.2.2.1
Metrics	i) Establish a baseline for the appropriate level of accuracy and precision for estimating remaining useful life in physics-based and data-driven simulations for different subsystems. As available, incorporate guidance from the MDAO IDG in Fundamental Aeronautics in determining quantification of these numbers. Quantification of desired prediction accuracy and precision for different subsystem is published at level 3. (FY09Q3) ii) Develop rigorous mathematical approaches for uncertainty representation and uncertainty management as applied to failure prognosis. Develop methods to shrink the uncertainty bounds of prediction of damage progression by 50% as measured from the initial prediction to the end of life. (FY11Q4)		
Metric Rationale	This is a notional average improvement that is expected for the different subsystems. The actual improvement achievable is – among others – a function of the availability of sensors on the subsystem, the noise content, the fidelity of the model, the uncertainty of future load and environmental conditions.		
1.2.4.1	Validated models of flight computer component failure, damage characterization, damage mitigation, and impact on flight safety.	FY09Q3 FY10Q1	1.2.2.1
Metrics	(i) Develop and characterize the performance of models and methods to detect, diagnose, predict, and mitigate selected flight computer component failures and damage and prognosticate impact of failure and/or successful recovery on aircraft safety state assessment; includes prediction and mitigation modeling relative to the effects of harsh environments on closed-loop system performance of a flight control system with functionality distributed across multiple hardware platforms and/or software partitions (baseline activity that will directly support metric 2 below) FY09Q1 (ii) Demonstrate application of these models and methods for detection, diagnosis, and prognosis of representative flight computer faults through analysis, simulation, or		

	experimentation with less than 1% false positive rate while improving false negative rate by 25% over baseline performance as determined in metric 1. FY10Q3
Metrics Rationale	Flight computer component failure modeling must encompass a wide variety fault manifestations. The demonstration metrics provided are notional and will be adjusted based on the results of the characterization effort in Metric (i).

IVHM 1.3 Advanced Analytics and Complex Systems

Problem Statement: The fulfillment of the IVHM project's goal requires the ability to transform the vast amount of data produced by the aircraft and associated systems and people into actionable knowledge that will aid in detection, diagnosis, prognosis, and mitigation at levels ranging from the aircraft-level, to the fleet-level, and ultimately to the level of the national airspace. The goal of this Level 1 activity is to produce tools that enable this transformation by leveraging the vast amount of available data in the best way possible.

Research Approach: The data produced by the aircraft and associated systems and people are vast, are in numeric and textual forms, have varying levels of quality, and represent operations at levels ranging from individual aircraft components up to the national airspace. We will develop methods to efficiently leverage this vast amount of data to enable detection, diagnosis, prognosis, and mitigation. The methods will use the vast amount of available data as much as possible to reduce the burden on human experts while incorporating their inputs. In this way, our work will be complementary to the work being done in the Modeling element. Together, we will use the best combination of domain expert knowledge and data to yield the best health assessment tools. The three sub elements of this element are Data Mining, Decision Science, and Adaptive Reconfiguration.

Data Mining

The success of the IVHM project relies, in part, on the ability to detect anomalies, diagnose problems, and make prognostic and mitigation decisions based on large amounts of heterogeneous data from a variety of systems, subsystems, and components. A current typical data set arising from one flight of a commercial aircraft may consist of nearly 1000 continuous and discrete quantities. The Data Mining sub element will develop tools that convert these data into actionable information for detection, diagnosis, and prognosis for three of the types of faults addressed in this project: slow-progressing, fast-progressing, and incipient. Numerous existing data mining methods have trade-offs between accuracy and speed. Clearly, for incipient faults, speed is critical, therefore, we would only want the level of accuracy required to determine whether there is a fault (e.g., if a sensor value being greater than a threshold indicates a fault, then the system should only check for that). On the other hand, for slow-progressing faults, data mining methods have can take more time to make more accurate assessments. Additionally, "accuracy" may mean different things in different situations. For example, if two explanations for a fault have equal severity and the same mitigation strategy, then diagnosing which of those two faults is present may be unnecessary - just knowing that either of those two faults is present may be sufficient. We will perform research with the aim of finding, and developing as needed, data mining methods that are the most flexible in terms of the accuracy metrics used and the trade-offs between accuracy and speed.

The previous paragraph discussed our strategy for developing data mining methods for IVHM at the flight level. However, these methods will be trained using large repositories of data covering a long enough period of time that they will also be used for assessing trends in fleet-level and system-level health, where “system” here refers to the overall air traffic system. We will also leverage additional data that can be used for system-level health assessment. For example, many commercial airlines maintain a repository of sensor data from their aircraft in large data warehouses along with text reports or narratives that describe safety incidents that may have occurred during flight. The text reports may also include maintenance logs and operational manuals regarding the aircraft. These data sources represent a rich and diverse set of information that can be used for system-level health assessment, trend analysis, and mitigation. We will develop methods that enable all these data to be leveraged at the same time to enable better trend analysis of system health. We expect that these methods will also help in the creation of simulations and other methods for the projection of these trends into the future and prediction of how new technological developments will alter these trends. Our methods will also serve as “prior distributions” in the work in the Bayesian Modeling Techniques sub element of this project. This study of system-wide health and the data mining tools resulting from this work will form an integrated capability for sharing information across the aviation community to enable continuous system-wide safety-risk assessment for the benefit of and access by the entire aviation industry. Therefore, these tools are applicable to achieving the goals of NASA’s collaboration with the FAA on Aviation Safety Information Analysis and Sharing (ASIAS).

As identified in the ASIAS Procedures and Operations Plan Section 3.0, Issues Analysis Process, a key requirement that arises in the development of data mining tools is the need to develop and test them on data representative of the real-world, proprietary and sensitive data sets. This development occurs in facilities (e.g., NASA) that cannot provide adequate protection of proprietary and sensitive data sets. Therefore, we plan to develop an emulator that will make ‘fake’ datasets in support of ASIAS tool development. This ‘fake’ data will use real-world data to capture important statistical properties while minimizing the ability for anyone to reverse engineer the results or identify any sensitive attributes of its sources.

Achieving the attributes required for ASIAS tool development poses significant technical challenges for development of this emulator, such as:

1. Capturing useful statistical properties: The emulator should create a fake dataset which exhibits similar statistical properties of real-world data important to ASIAS data-mining tool development. This will also require strategic planning in coordination with the ASIAS Issue Analysis Team of the capabilities desired in new ASIAS tools.
2. Proprietary Data Protection: Minimize the probability that the non-public real-world data can be reverse engineered from the emulated data.
3. Injecting fault scenarios: Many anomalies in the real-world data will need to be removed from the fake data to minimize the probability of reverse engineering; likewise, some faults may be very rare. Therefore, the emulator will need to inject fault scenarios of interest into the emulated data.

The tradeoff between the requirements to capture useful statistical properties of the real-world data while minimizing the probability of reverse engineering poses a significant technical challenge that will be addressed through a combination of modeling the statistical properties of real-world data and combining it with simulation capabilities. It is worth noting that this is a very complex task involving areas in machine learning, data mining, simulation methods, statistics, and probability theory. Simulation or emulation of the flight data is not equivalent to modeling the aircraft. Thus, standard single aircraft simulators are not adequate to capture the complexities of the data present in real-world, operational, flight-recorded data.

Decision Science

The data mining sub element assumes a process of collecting data in varying quantities and transforming it into actionable knowledge for detection, diagnosis, prognosis, and mitigation. However, in addition to assessing the health of a system, understanding the uncertainty in that assessment is critical. Also, for the sake of efficiency, health assessment methods should only use the data that helps improve health assessment in some important way such as reducing uncertainty. To that end, health assessment methods should be able to query the sensor system for the information most helpful to them at any given time.

There are several current research efforts that can help in developing such health assessment methods. Within NASA's Science Mission Directorate, the Earth Science Technology Office is funding numerous projects in the area of Sensor Webs, where the goal is to develop methods that can move sensors, turn them off, change their fidelity, and make other changes with the idea of leveraging the sensors in the best way possible to solve science problems while minimizing costs due to power, sensor wear, data storage, etc. The disciplines of probabilistic planning and decision-theoretic planning attempt to solve the problem of interest (e.g., diagnosis with lowest uncertainty) while taking into account the uncertainty of the environment and the costs of taking diagnostic actions. There is some work in decision-theoretic diagnosis or troubleshooting that attempts to find the sequence of query actions that achieves the best trade-off between lowest diagnostic uncertainty and lowest cost. We will investigate methods in these various disciplines that will work for the different time scales on which different faults and trends operate. For example, decision-theoretic planning enables the use of different time horizons. For incipient or fast-progressing faults, a short time horizon would be most appropriate, since the query action that most rapidly reduces uncertainty would likely be chosen. On the other hand, for slow-progressing failures, a longer time horizon would be best, whereby a sequence of actions that takes longer to determine but is less costly and is the most informative would be chosen. Our work in this sub element will tie in with the Bayesian Modeling Techniques element because Bayesian modeling techniques have a mathematically rigorous way of representing uncertainty in the environment and in the health state estimates. Recent research has examined the use of Bayesian networks to find the measurements most informative to diagnosis. We will examine this research and assess its use in finding the faults of interest to the IVHM project.

Adaptive Reconfiguration

Modern aircraft are comprised of many subsystems, with many interactions between those subsystems. Accordingly, optimal management of the health of an aircraft involves managing the interactions between its subsystems to maintain the best possible aircraft health for the longest period of time.

A simple example arises if a single subsystem of the aircraft behaves anomalously. Ideally, the IVHM system could directly modify the behavior of the other subsystems to compensate for the first subsystem's misbehavior and thereby maintain the overall health of the aircraft. However, in general such direct modification is not allowed; instead, the IVHM system must modify the interactions among those subsystems. More generally, it may be that no single subsystem behaves anomalously, but the aircraft's overall behavior is anomalous. Again, the IVHM system typically cannot directly modify the behavior of the subsystems to compensate for this overall anomalous behavior, but instead it must modify the interactions between the subsystems to rectify the anomalous behavior.

Some examples of such modifications to the interactions between subsystems are distortions to data sent from sensors into subsystems, distortions to command data sent from subsystems, modifications of which subsystems communicate with which other subsystems, and modifications of externally set operating parameters of subsystems. Typically such management of subsystem interactions must be done in an adaptive manner. Moreover, usually there is limited modeling information concerning the operation of the subsystems and/or their interactions. Rather, what is known is the tasks assigned to the subsystems, together with online data of how they behave. We will investigate and develop methods to perform such modifications in a way that balances the trade-offs between appropriate characteristics such as performance, current subsystem and aircraft health, and future aircraft health (maximizing remaining useful life, minimizing number of failed components, and other relevant metrics). We will build on ongoing preliminary work that can, for example, be used to adjust inputs to two interacting subsystems in such a way that if either of them or both of them are in a degraded operating state, the overall system health is maintained even though each subsystem may be independently attempting to adapt to its own difficulties and/or those of the other subsystem.

We will also investigate and develop the above-described methods for adaptive reconfiguration at the system level by building on previous work on the use of distributed multi-agent systems methods for air traffic control. Our methods will balance trade-offs between appropriate characteristics such as maintenance of minimum aircraft separation, minimizing delays, and the least interference when an aircraft has a problem and needs to land quickly. We will work with the Airspace Systems Project to develop methods that are most likely to aid air traffic controllers and other key personnel in managing the Next Generation Air Transportation System.

IVHM 1.3 Advanced Analytics and Complex Systems			
Number	**Title**	**Year**	**Dependencies**
1.3.1.1	Demonstrate automated anomaly detection in an offline mode on large heterogeneous datasets from multiple aircraft. Provide comprehensible "reasons why" an anomaly is tagged as such.	FY11Q2	1.3.1.3, 1.3.1.4, 1.3.3.1, 1.3.5.1
Metrics	Demonstrate at least linear scalability in terms of data set size and demonstrate that at least 3 out of 4 surveyed experts agree that at least one identified anomaly has potential		

	operational significance (assuming that access to real-world data is possible). Minimum data set size for testing should be 10 TB.		
Metric Rationale	In the worst case, all data may need to be examined at least once, which mandates linear or worse scalability. False positive rates are a function of the system on which anomaly detection is performed. The operational significance and meaning of anomalies can only be assessed by domain experts, but can be assisted by appropriate tools. In this context, ‘heterogeneous’ refers to data including continuous and discrete attributes, and offline mode indicates that the algorithms will examine fixed data sets (i.e., without needing to update with each arrival of new data) and may make multiple passes over the data sets.		
1.3.1.2	Demonstrate automated anomaly detection on single aircraft systems and subsystems together with comprehensible “reasons why” an anomaly is tagged as such.	FY11Q4	1.3.3.1, 1.3.5.1
Metrics	Demonstration of anomaly detection capabilities such that detection occurs with a false positive rate of nominally less than 5%.		
Metric Rationale	False positive rates are a function of the system on which anomaly detection is performed.		
1.3.1.3	Develop and demonstrate anomaly detection algorithms for continuous data sources in: (i) offline mode on large data sets from multi-aircraft data systems and (ii) near-real time mode on single aircraft systems and subsystems	FY08Q4	
Metrics	Develop algorithms that can detect anomalies in continuous data streams at least 2 times faster than standard benchmark algorithms while preserving the accuracy of the algorithm with respect to the area under an appropriate ROC curve.		
Metric Rationale	In addition to accuracy, speed is important to make regular use of these methods easier and more practical. A reduction of running time in half is a challenging but reasonable metric in line with what is observed in the literature.		
1.3.1.4	Generation of simulated data for testing of detection, diagnosis, and prognosis of anomalies on continuous, discrete, and combined data sets and delivery to public. (WAYPOINT)	FY08Q4	
Outcome	At least four sources of simulated data modeled on the statistical properties of real continuous, discrete, and combined continuous and discrete data have been made fully accessible to all participating parties with no restrictions on publications of results of their analyses.		
1.3.2.1	Implement and benchmark improved algorithms for fault diagnosis in offline mode on large heterogeneous data sets (continuous, discrete, and text) from multi-aircraft data systems.	FY10Q4	1.3.3.1, 1.3.2.3
Metrics	Demonstration of at least two anomaly diagnosis systems that have a detection accuracy that is at least 15% more accurate with respect to the area under an appropriate receiver operator characteristic (ROC) curve compared to standard benchmark methods to be		

	established.		
Metric Rationale	ROC curves are functions of the false positive and false negative rates; therefore, measuring anomaly detection algorithm accuracy by ROC curves rewards balancing the two rates over improvement in one rate at the expense of the other. 15% is a nominal metric here – different systems have different current and achievable levels of accuracy.		
1.3.2.2	Implement and benchmark decision-theoretic algorithms for fault diagnosis in offline mode on large heterogeneous data sets from multi-aircraft data systems.	FY11Q2	1.3.3.1, 1.3.2.1
Metrics	Demonstration of decision-theoretic algorithms for fault diagnosis that return diagnoses with at least 15% greater accuracy with respect to the area under the ROC curve and the same or better running time compared to what is achieved in 1.3.2.1.		
Metric Rationale	The goal of the work in decision science is to be more efficient; therefore, in offline mode when rapid response is unnecessary, greater accuracy should be achievable in the same time.		
1.3.2.3	Develop techniques to classify text reports into anomaly categories.	FY08Q4	
Metrics	Produce an algorithm that classifies text reports into anomaly categories at least nominally 10% better than the best published benchmark in terms of the area under the ROC curve.		
Metric Rationale	This is a notional expected improvement. The actual improvement achievable and improvement required are a function of the particular system(s) represented by the available data.		
1.3.3.1	Establish user requirements to be used in future milestones. Develop appropriate accuracy rates for detection, diagnosis and prognosis for offline numeric and text data from multi-aircraft systems and for near-real time data from single aircraft systems and subsystems.	FY09Q2 and each year thereafter	4.2.1, 4.2.2, 4.2.3
Outcome	Using benchmark data sets develop nominal false positive and true positive rates for each of the following data types: continuous, discrete, and combined continuous and discrete signals. Also document state of the art for appropriate ROC curves. Nominal false positive and true positive rates need to be developed separately for each system for which data is supplied. For future text analysis activities, develop and document appropriate metrics for future text analysis milestones.		
1.3.3.2	Demonstrate automated anomaly prediction in an offline mode on data in large heterogeneous datasets from multiple aircraft. Provide comprehensible “reasons why” an anomaly is tagged as such	FY11Q2	1.3.3.1
Metrics	Demonstrate at least linear scalability in terms of the size of data set size and demonstrate that at least 3 out of 4 surveyed experts agree that identified anomalies have operational significance and are meaningful. Minimum data set size for testing should be 10 TB.		
Metric Rationale	Time horizons are a function of the system on which anomaly detection is performed. The operational significance and meaning of anomalies can only be assessed by domain experts, but can be assisted by appropriate tools.		
1.3.3.3	Demonstrate automated anomaly prediction in near-	FY11Q2	1.3.3.1, 1.3.3.2

	real time on single aircraft systems and subsystems, together with comprehensible “reasons why” the anomalies were tagged as such.		
Metrics	Demonstration of anomaly prediction capabilities such that detection and prediction occur within an appropriate time horizon which is nominally 2 seconds with a false positive rate of nominally less than 5%.		
Metric Rationale	Time horizons are a function of the system on which anomaly detection is performed. The operational significance and meaning of anomalies can only be assessed by domain experts, but can be assisted by appropriate tools.		
1.3.3.4	Develop methods to predict anomalies in combined continuous and discrete data sources.	FY10Q2	1.3.3.1
Metrics	Demonstrate improvement of at least 10% with respect to prediction horizon set in 1.3.3.3.		
Metric Rationale	This is a notional improvement. The actual improvement achievable and improvement required are a function of the particular system(s) represented by the available data.		
1.3.3.5	Implement and benchmark decision-theoretic algorithms to support prognosis in near real-time mode for a single aircraft subsystems.	FY11Q4	1.3.3.1, 1.3.2.2
Metrics	Demonstration of decision-theoretic algorithms for fault diagnosis that return diagnoses at least twice as fast but with comparable accuracy to what is achieved in 1.3.2.2.		
Metric Rationale	The goal of the work in decision science is to be more efficient; therefore, in near real-time mode when rapid response is needed, faster diagnoses should be achieved through judicious selections of data.		
1.3.4.1	Implement and benchmark algorithms to support reconfiguration, recovery, and redundancy management.	FY11Q2	1.3.3.1
Metrics	Demonstration of algorithms for reconfiguration, recovery, and redundancy management to mitigate failures for at least two subsystems injected with representative faults.		
Metric Rationale	To help prepare for future integrated tests, we will demonstrate adaptation following adverse events affecting at least two subsystems.		
1.3.5.1	Acquisition of at least three publicly available, real-world datasets each of at least 100 GB in size. (WAYPOINT)	FY08Q4	1.3.1.4
Outcome	Real flight-recorded data are considered proprietary by the airlines that own them so that they are not publicly available for researchers to use in development of new analytical tools. These data sets will be used to begin the research and development process on the emulator. Subsequent validation will be required on real-world, fleet-level aircraft data. The success of subsequent milestones requires that NASA be given access to a substantial amount of real-world data.		
1.3.5.2	Demonstration of an emulator of flight-recorded data that has at least 5 significant statistical properties of real-world flight recorded data and is at least 1 TB in total size.	FY11Q2	1.3.5.1
Metrics	Demonstrate that emulator-generated data satisfactorily minimizes the potential for reverse engineering to identify the sources of the emulated data and still have sufficient fidelity to enable the development of advanced tools for analyzing real flight data to		

	discover unexpected anomalies. Resultant algorithms based on emulator-generated data produces results when applied to real data that are considered reliable, viable, and understandable by domain experts in, at least, 75% of the trials. The ASIAS Executive Board will be requested to provide at least 3 domain experts to assist in the evaluation.
Metric Rationale	Real flight-recorded data are considered proprietary by the airlines that own them so that they are not publicly available for researchers to use in development of new analytical tools. An emulator that protects the identity of the original data source(s) and yet can produce publicly available, high fidelity data will enable the development of tools that could be useful to ASIAS.

IVHM 1.4 Verification and Validation

Problem Statement: Successful infusion of vehicle health management necessitates verification and validation of highly complex and integrated systems that employ advanced technologies in areas such as sensors, artificial intelligence, data fusion, diagnostics, and prognostics. The use of these technologies for detecting critical faults in propulsion, flight, and airframe systems is without precedent in civil aviation, and will require a high level of confidence that the diagnosis and predictions made by onboard health management systems are correct and reliable. Moreover, because of the large number of parameters and complex sub-system interactions inherent in health management systems, it will be exceptionally difficult to use current approaches that rely upon human inspection, simulation, and testing. New tools and methods are necessary to build trust in future IVHM systems.

Research Approach: We will develop processes and underlying methods and tools to provide a comprehensive approach to verification and validation (V&V) that will ensure safe and reliable application of IVHM technologies to civil aviation. The resulting methods and tools will be made publicly available to assist the aerospace community in demonstrating compliance with regulations and to improve safety. Research challenges for V & V of IVHM technologies include: 1) Verifying that the observables of a physical system are sufficient to identify defined classes of faults for detection systems; 2) verifying and validating detection, diagnosis, and prognosis accuracy for highly non-linear and non-Gaussian failure phenomena; 3) enabling certification of *automated* mitigation techniques; 4) verifying and validating software-driven diagnosis methods; and 5) establishing methods to perform V&V for software health management systems. Development in techniques and tools for the specification, design, and verification of IVHM software systems is needed, and the approach will include advancements in symbolic model checking, theorem proving, compositional verification, static analysis, and runtime integrity monitoring.

IVHM 1.4 Verification and Validation

Number	**Title**	**Year**	**Dependencies**
1.4.5.1	Demonstration of compositional verification framework that provides assurance that key system safety properties are met.	FY08Q4 and yearly FY10Q2 FY11Q2 FY12Q3	
Metrics	1. Collaborate with the multi-agency High Confidence Software and Systems (HCSS) coordinating group of the Networking and Information Technology Research and Development program in the identification of suitable approaches; participate in HCSS CG-Sponsored and Co-Sponsored Briefings, Planning Meetings, and Workshops; key activities and decisions reported within the IVHM quarterly reporting framework (WAYPOINT, FY08Q4 and yearly). 2. Document one hypothetical design whose verification is intractable due to an exponentially large state space or other computational issue using existing monolithic approaches. (FY10Q2) 3. Demonstrate compositional verification methods on the above design via a framework which ensures that individual software components individually satisfy their safety requirements, and, when connected, integrated, and assembled, satisfy global safety properties; (FY11Q2) 4. Show that these new compositional techniques establish safety properties that otherwise could not be established using existing monolithic approaches. (FY11Q2) 5. Show that these new compositional verification methods provide an equal or greater level of integrity as provided by current assurance approaches. (FY12Q3)		
Metric Rationale	Demonstrating on a realistic, and otherwise intractable to verify, design provides for a representative case for assessment by assurance organizations. Coordination and information exchange across the research community is provided through collaboration with a multi-agency R&D program – a program that is focused on high-confidence systems with emphasis on compositional verification research approaches for the assured confidence of complex systems.		
1.4.5.2	Demonstration of formal verification and automated testing for diagnostic and monitoring systems using hybrid abstraction.	FY09Q4 FY10Q4 FY11Q1 FY11Q4	
Metrics	1. Develop and document concepts and procedures for nonlinear arithmetic. (FY09Q4) 2. Integrate 100% of the successful new procedures into relevant formal verification tools. (FY10Q4) 3. Identify a realistic design requiring both discrete and continuous analysis and enumerate requisite safety properties (FY11Q1) 4. Machine-checked formal proof of enumerated key properties for the design identified in metric 3. (FY11Q4)		
Metric Rationale	The machine-checked formal proof provides a high level of confidence in the applicability of the newly developed procedures and tools to real problems requiring both discrete and continuous analysis.		

Acronyms

API	Associate Principal Investigator
ASIAS	Aviation Safety Information Analysis and Sharing
ASMM	Aviation Safety Measurement and Modeling
BMOD	Bill of Material Object Damage
CAST	Commercial Aviation Safety Team
DARPA	Defense Advanced Research Projects Agency
DFRC	Dryden Flight Research Center
DoD	Department of Defense
EIDD	Electrical Impedance Damage Detection
EPS	Electrical Power Systems
ETDP	Exploration Technology Development Program
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Control
FOD	Foreign Object Damage
HIRF	High-Intensity Radiated Fields
HM	Health Management
IEEE	Institute of Electrical and Electronics Engineers
IIFD	Integrated Intelligent Flight Deck
IRAC	Integrated Resilient Aircraft Control
ISHM	Integrated Systems Health Management
IVHM	Integrated Vehicle Health Management
JPDO	Joint Planning and Development Office
JSF	Joint Strike Fighter
MAPSS	Modular Aero-Propulsion System Simulation
MEMS	Micro-Electromechanical Systems
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
NTSB	National Transportation Safety Board
OGA	Other Government Agencies
PHM	Prognostics Health Management
PRA	Probabilistic Risk Analysis
R&D	Research and Development
RF	Radio Frequency
SAFETI	Systems and Airframe Failure Emulation Testing and Integration
SOA	State of the Art
V&V	Verification and Validation
X-FEM	Extended Finite Element Model

Change Record

Rev.	Effective Date	Description
00	4-21-20008	Baseline. Approved Tech Plan
01	8-14-2008	Provided clarification on collaboration with other programs/ projects and on the following milestones: 2.1.4.1, 2.3.2.1, 2.4.5.2, and 1.1.1.8. Inserted corrected level diagram. Updated PART/IBPD table. Changed due dates on 4.4.1 and 1.1.1.9 to better align with NRA cycle (ongoing and planned awards) Inserted this Change Record.