

NASA/TM—2010-216911



Assessment of the State of the Art of Integrated Vehicle Health Management Technologies as Applicable to Damage Conditions

Mary S. Reveley
Glenn Research Center, Cleveland, Ohio

Tolga Kurtoglu
Mission Critical Technologies, Moffett Field, California

Karen M. Leone
ASRC Aerospace Corporation, Cleveland, Ohio

Jeffrey L. Briggs and Colleen A. Withrow
Glenn Research Center, Cleveland, Ohio

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Telephone the NASA STI Help Desk at 443-757-5802
- Write to:
NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320



Assessment of the State of the Art of Integrated Vehicle Health Management Technologies as Applicable to Damage Conditions

Mary S. Reveley
Glenn Research Center, Cleveland, Ohio

Tolga Kurtoglu
Mission Critical Technologies, Moffett Field, California

Karen M. Leone
ASRC Aerospace Corporation, Cleveland, Ohio

Jeffrey L. Briggs and Colleen A. Withrow
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at <http://gltrs.grc.nasa.gov>

Assessment of the State of the Art of Integrated Vehicle Health Management Technologies as Applicable to Damage Conditions

Mary S. Reveley
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Tolga Kurtoglu
Mission Critical Technologies
Moffett Field, California 94035

Karen M. Leone
ASRC Aerospace Corporation
Cleveland, Ohio 44135

Jeffrey L. Briggs and Colleen A. Withrow
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

A survey of literature from academia, industry, and other Government agencies assessed the state of the art in current Integrated Vehicle Health Management (IVHM) aircraft technologies. These are the technologies that are used for assessing vehicle health at the system and subsystem level. This study reports on how these technologies are employed by major military and commercial platforms for detection, diagnosis, prognosis, and mitigation. Over 200 papers from five conferences from the time period of 2004 to 2009 were reviewed. Over 30 of these IVHM technologies are then mapped into the 17 different adverse event damage conditions identified in a previous study. This study illustrates existing gaps and opportunities for additional research by the NASA IVHM Project.

Introduction

Purpose of Study

NASA's Integrated Vehicle Health Management (IVHM) Project is one of four projects within the Agency's Aviation Safety Program (AvSafe) in the Aeronautics Research Mission Directorate (ARMD). The IVHM Project conducts research to develop validated tools and technologies for automated detection, diagnosis, and prognosis to mitigate 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 (Ref. 1). The purpose of this study is to review literature from academia, industry, and other Government agencies to assess the state of the art of IVHM research and technologies applicable to the specific adverse event conditions documented in the adverse events table of the project plan (Ref. 1).

Overview of Study Contents

- This report presents results of a survey of the literature from academia, industry, and other Government agencies to assess the state of the art in current IVHM technologies and to discuss

how they are employed by major military and commercial platforms for detection, diagnosis, prognosis, and mitigation. The results are summarized into the 17 documented adverse event example damage conditions. A brief explanation of these example damage conditions is given. In addition, a summary illustrates existing gaps and opportunities for the NASA IVHM Project.

Adverse Event Example Damage Conditions Related to Integrated Vehicle Health Management (IVHM) Fault Type

A list of example damage conditions as they relate to given adverse event fault types are presented in Table 1. It was built upon the results of an examination of the most recent statistical and prognostic incident and accident data that was available. In the analysis, publicly available National Transportation Safety Board (NTSB) accident, Federal Aviation Administration (FAA) accident and incident data, and Aviation Safety Reporting System (ASRS) incident data were examined, and 17 example damage conditions were documented (Ref. 2).

TABLE 1.—INTEGRATED VEHICLE HEALTH MANAGEMENT (IVHM)
ADVERSE EVENTS TABLE

Adverse event type	Example damage condition
Incipient faults	1. Icing conditions in propulsion system
	2. Fault of power electronics
	3. Turbine engine bearings
Slow progression faults	4. Fatigue cracks on metallic airframe structure
	5. Delamination in composites
	6. Hydraulic failures
	7. Air conditioning and pressurization faults
Intermittent faults	8. Oil and/or lubrication failures
	9. Wire chafing failures
Cascading faults	10. Power system faults
	11. Control surface faults (aileron, rudder, or elevator)
	12. Instrumentation, communication, and navigation failures
	13. Fuel system faults
Fast progression faults	14. Engine stall or faults in turbomachinery
	15. Landing gear faults
	16. Brake and/or anti-skid system faults
	17. Lightning- and radiation-related avionics faults

The purpose of the adverse event table (Table 1) is to provide guidance to the IVHM Project about critical research areas in health management technologies. It may be noted, that this table is expected to change as the IVHM Project matures and future technologies and trends become clear. The first version of the initial adverse events table was constructed by collecting data gleaned from findings within the ASRS, FAA, and NTSB databases and is shown in Table 1 (Ref. 2).

The adverse event types are categorized into five classes based on the overall remaining useful life of the affected system, subsystem, or component defined as follows:

- Incipient fault.—Faults that are hard to detect and differentiate due to extremely slow degradation in performance.
- Slow progression fault.—Faults that are very hard to detect; gradual degradation in performance.
- Intermittent fault.—Faults that do not degrade but instead manifest themselves in a recurring fashion.

- Cascading fault.—Faults that may have a single-root cause yet progress to create faults in other systems, subsystems, or components.
- Fast progression fault.—Faults that have a limited precursor signature but show rapid degradation.

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

State-of-the-Art Assessment of Integrated Vehicle Health Management (IVHM) Research and Technologies

This section contains the results of the literature survey conducted to address this expected outcome. The findings for each adverse event example damage condition are summarized below.

1. Icing conditions in propulsion systems

Icing is one of the adverse events that has attracted a significant amount of research ranging across IVHM (Ref. 3). Starting with detection, the state of the art includes both the detection of icing conditions in the airspace using ground-based models, as well as in situ detection of ice accretion on the aircraft. Researchers at the National Center for Atmospheric Research have developed the forecast icing potential algorithm, which uses data from the National Center for Environmental Prediction to calculate icing potential in the three-dimensional environment (Ref. 4). If integrated into the flight deck, this could be used by pilots to avoid areas of high icing potential. Another method of detection is a joint venture between NASA and the U.S. Army to use ground-based Ka- and X-band radar to locate icing conditions in cloud formations, but this is also not yet integrated into any flight system (Ref. 5). One method currently being investigated for detection of ice accretion on the aircraft is time domain reflectometry (TDR). With this method, electromagnetic waves are transmitted, and when they are received, the presence of ice is detected based on the dispersion of the waves. Currently, this technology is still in the feasibility study stage (Ref. 6). In terms of prognosis, there are numerous computational models that are used to predict the growth of ice both on the airframe and on surfaces in the propulsion system (Ref. 7). In addition to prognostic models of ice accretion, models also exist to predict the degradation of flight controls as icing conditions develop (Ref. 8). In terms of mitigation, one method that has been found effective was introduced by General Electric (GE) in 1996. They found that flameout due to icing frequently occurred on descent, between an altitude of 20 000 and 10 000 ft. GE changed the engine control unit variable bypass valves logic to increase ice extraction from booster core and inlet in this range of altitudes, and no events have occurred on aircraft where this change was made (Ref. 9).

2. Fault of power electronics

Monitoring the deterioration of components in electronic systems is much harder than mechanical systems (Ref. 10). There has been a recent increase in developing methods and technologies for prognostics and health management of electronic components such as power system components, avionics, and solder joints. For diagnostics of electronic components expert systems, neural networks and fuzzy logic systems are used (Ref. 11). Bayesian diagnostic models are also used for diagnosing faults in electronic systems (Ref. 12). Solder joint faults are proving to be one of the main failure sources of electronic components. Thus, solder fatigue modeling and monitoring technologies are used to monitor small cracks that develop and propagate in the microstructure of solder joints due to thermal loading and/or aging. The changes in the material microstructure due to aging are used by some researchers to predict remaining useful life of the solder joints of electronic components (Refs. 13 and 14). Other

prognostic methods have been proposed for various critical electronic components including digital electronic boards (Ref. 15), silicon carbide packaging (Ref. 16), integrated circuits (Ref. 17), and power actuators (Ref. 18).

3. Turbine engine bearings

Bearing health monitoring is critical to the performance of turbomachinery. Diagnostic technologies for rolling elements are relatively well developed. Among these are stress wave analysis, which provides real-time measurement of friction and mechanical shock in bearings. This high-frequency acoustic sensing technology filters out background levels of vibration and audible noise, and provides a graphic representation of machine health (Ref. 19). Acoustic emission technologies also indicate bearing stress. Robust laser interferometer (RLI), an alternative technology to acoustic emissions, has also demonstrated use for bearing health monitoring (Ref. 20). Alternatively, accurate prediction of remaining life of bearings remains a challenge. Novel techniques for remaining useful life (RUL) estimation for bearings are in development especially those targeting incipient faults (Refs. 21 to 24). Smart bearings, although still at development stage, is another novel technology. If successfully developed, these bearings will have a number of unique features such as having all sensory and telemetry data built into the bearing, durability for higher temperatures, long-life, and compatibility with the operating environments (Refs. 25 to 27).

4. Fatigue cracks on metallic airframe structure

The current state of the art in detection methods for fatigue cracks on the metallic airframe structure mostly involves onground inspections. In terms of current fleet operation, this is usually done manually as a part of routine maintenance, which means a crack might be present for a while before it is identified. Various probe technologies are currently being investigated that would allow technicians to detect cracks that would not otherwise be visible. One such technology is eddy current inspection (ECI), which is a new method that produces a magnetic field on a material's surface to detect cracks, corrosion, heat effects, and thicknesses. ECI is effective on metallic surfaces, but is limited to the area directly below the instrumentation point (Ref. 19). For example, one probe uses eddy current to detect fatigue cracks underneath fasteners (Ref. 28). For onboard detection, piezoelectric transducers (PZTs) can detect crack via disruptions in stress waves sent through particular airframe structures in flight (Ref. 19). The feasibility of integrating this technology onto an aircraft is yet to be determined. Acoustic emission is another technology that is used for surface and inner structure crack detection and localization. This nondestructive evaluation technique involves monitoring for the emission of high-frequency vibration (>100 000 Hz) as an existing structural defect (crack) is stressed from the static loading of the system (Refs. 26, 27, and 30). In addition, induced positron analysis technologies can reliably detect and quantify tensile plastic strain damage induced by simulated and operational conditions in aerospace material specimens and components including metallic surfaces (Refs. 31 and 32). In the area of prognostics, numerous algorithms have been developed to predict the growth of cracks under various flight conditions (Ref. 33). Once a crack has been discovered, the current state of the art in mitigation normally involves patching or bonding with epoxy or selective reinforcement (Ref. 29). Some additional research has been done in terms of effective selective reinforcement and the types of fixes that can be implemented to slow the crack (Ref. 34). Still, none of these methods involves onboard solutions. Some condition-based mitigation methods exist that use materials through which cracks naturally propagate more slowly (Ref. 35). Another method of condition-based mitigation is dynamic controls that change the load spectra to lighten loads on fractured structures. This does not fix the crack but could help slow its progression until it could be fixed on the ground (Ref. 36).

5. Delamination in composites

The use of composite materials in structural design is becoming increasingly popular in aerospace applications because of the benefit of reduced weight without much compromise in strength and stiffness performance. Understanding composite material's principal mode of failure, delamination, has become

increasingly important (Ref. 37). Delamination may occur in the form of microcracks and voids, usually leading to macroscopic loss of stiffness and strength, followed by a catastrophic structural collapse. IVHM technologies for delamination encompass sensors that detect aging, unanticipated events such as impacts, and nondestructive inspection (NDI) tools for flaw identification and damage characterization. Specific sensors developed for onboard impact detection include PZT and fiber Bragg grating ultrasonic sensors, which can locate the point of impact (Refs. 19 and 38). Once impact is detected, NDI tool images are used to study the damage region, and modally selective sensors (i.e., lamb wave sensors (Ref. 39)) are used to monitor further damage growth. Different damage growth prediction methods are finally employed to estimate the remaining lifetime of the structure. These methods include the linear elastic fracture mechanics method, the cohesive fracture model, and delamination threshold load method (Ref. 40). Feature-based signal processing methods, and data-driven classification techniques are also proposed for damage detection and prediction (Refs. 41 and 42).

6. Hydraulic failure

Hydraulic systems are extremely important in aircraft, especially for positioning control surfaces and for operating landing gear. Linked closely with hydraulic systems that maneuver the control surfaces are actuators, as they are often driven by hydraulics. One problem that can occur in the hydraulic system is called cavitation. This phenomenon occurs when the pressure at the pump inlet is lower than the vapor pressure of the fluid, and it causes bubbles to form in the system. It is ideal to avoid this situation if possible, as it increases wear on the system. Researchers have developed a neural-network-based algorithm to detect cavitation using as inputs the electric current supplied to the pump motor and a voltage that can be used to determine the operational speed and output flow of the pump (Ref. 43). The cavitation data could possibly be fed to an adaptive control system to help increase the operational life of the hydraulic system. Another method of monitoring the health of hydraulic systems is vibration analysis of the hydraulic pumps. The algorithm uses the fundamental frequencies and harmonics of the pump and determines if it is operating normally or in a degraded state (Ref. 44). There are many types of hydraulic system faults that result in a small leak somewhere in the system. Small leaks can be present before they cause larger problems. If they are detected early, it is possible to prevent these problems. One method for detecting these faults involves online, model-based fault detection. Using the operational speed of the pumps, it is possible to determine the pressure that should exist at various points in the system. Models have been developed that use pump data and pressure sensors to determine if there are leaks in the system and where those leaks are located (Ref. 45).

Hydraulic actuators are being replaced with electromechanical actuators (EMAs) in future aircraft designs. In normal operation these are driven by electric power, but in high stress situations, during a jam, or when electric power to the actuator is disrupted, the hydraulic system supplies the power needed to operate the actuator. One problem that can occur in these actuators is called ball-jam where the moving part containing the ball bearing gets stuck somehow, preventing the control surface from moving. The majority of detection, diagnosis, and prognosis technologies in regards to ball-jam in EMAs are model based. Various modeling techniques are used to detect malfunctioning EMAs, as well as for the prediction of time to fail for the entire system (Ref. 46). Although models have been created, the majority of the work is still done by technicians on the ground. Technologies are being developed that use flight control data and will be able to deliver gray-scale, as opposed to pass-fail feedback to maintenance technicians. Another technology for in-flight mitigation of ball-jam is the development of hybrid electromechanical/hydraulic actuators. These actuators run mechanically in normal operation, but a parallel hydraulic system kicks in when extra power is needed because of heavy loads or a ball-jam. It is not certain that the hydraulic system will fix the jam, but it is one method of in-flight mitigation (Ref. 47).

7. Air conditioning and pressurization faults

Researchers have produced fairly extensive prognostic models predicting the failure of various components in the pressurization system using Weibull distributions. These distributions are based on a power law relationship in which the probability of failure increases with flight hours (Ref. 48). It is also

noted that 61 percent of component failures in this system are related to the water separator, so a significant amount of risk can be reduced by focusing on this component (Ref. 49). However, in the future this failure in particular may have a decreased relevance. Currently, pressurization systems use either preconditioned air from the ground or bleed air from the engine, which requires a water separator. As aircraft manufacturers move towards more electric aircraft, such as the Boeing 787, they may use electric fans to pressurize the cabin where no water separators are required. Reasons for the transition to an electric architecture include significant maintenance cost as well as reliability advantages (Ref. 84). Even if these faults are eliminated, they would then need to focus more attention on electrical and wiring faults, and the powerplant will need to produce four times as much electricity.

8. Oil and lubrication system failures

The main problems associated with aircraft oil and lubrication systems arise from clogged filters, pressure anomalies, and water in the oil. Pressure anomalies can result from multiple causes including low levels of lubricant and clogged filters. The health of this aspect of the lubrication system is monitored by pressure sensors that relay information to the pilot. Pilots are trained to recognize and adjust for various situations. Another method that is used to monitor the loss of lubricant in an engine involves a vibration analysis of moving engine components. Different vibration signatures arise as the level of lubricant in the system varies. This method is currently used by the U.S. Army for light armored vehicles, but might also be applied to aircraft (Ref. 30). Faults in the oil system, such as a clogged filter, are often indicators of failures in components lubricated by the system. For example, as a moving part is worn down over time, particulates accumulate in the oil that lubricates it, and this can clog the filter. Also, more than just getting worn down, structural failures in components might cause larger pieces of debris to accumulate in the system. By analyzing the oil in the system for composition and size of particulates, information about the health of lubricated components and of the oil system itself can be obtained. In 1995, the U.S. Army mandated that its aircraft undergo this type of analysis on a regular basis (Ref. 50). Jet-Care has also commercialized the process by analyzing oil and filter samples for operators. Results of the analyses include system health diagnosis and a prognosis for suggested maintenance (Ref. 51).

9. Wire chafing failures

Visual inspection is the most common technique to detect wire chafing in current aircraft. This failure increasingly occurs as aircraft fleets age; 43 percent of electrical system mishaps are related to connectors and wiring (Ref. 52). As we move towards more electric aircraft, the increased amount of wiring will only make this failure more frequent. Wire placement is a big driver of these problems, because wire bundles closer to hydraulics or airframe structures are more prone to chafing. One simple method of mitigation is to use standoff clamps to hold wire bundles away from these structures (Ref. 53). Some more advanced methods of detection use differences in impedance to detect flaws in insulation before the conductor inside is harmed and shorts occur. However, one drawback to this method is that it does not help locate the area of the wire failure (Ref. 54). Innovative Dynamics planned an integrated test of a wire chafing sensor in a Goodrich wiring harness. As the sensor became chafed, it made maintenance technicians aware of the problem before the actual wires were harmed (Ref. 55). Another detection method that is especially promising because it is used to both detect and locate faults in a wire harness is called the pulse-arrested spark discharge. This method can find faults that would only produce undetectable changes in impedance, and it can be used for multiple other purposes in addition to detection of wire chafing (Ref. 56). Another new type of sensing technology involves wrapping fiber optic cables around a wire bundle. As the fiber becomes chafed or breaks, the decreased transmission or short is easily detectable, as well as the location on the wire bundle (Ref. 57). As electric aircraft technology advances, wireless networks may be able to eliminate a lot of these failures (Ref. 58). Previously introduced RLI technology also has demonstrated potential for electrical wiring health monitoring (Refs. 20 and 59). Finally, previously introduced TDR is another method that can be used to measure changes in electronic wiring interconnect system characteristic impedance for detection of chafe, nicks, and corrosion defects (Ref. 60).

10. Power system faults

Both military and commercial aerospace systems are becoming increasingly dependent on electrical power as systems move towards the more electric aircraft concept. This novel architecture relies on digitally controlled power distribution to provide power to flight critical subsystems such as avionics and fuel. This increasing dependence on electrical power necessitates the development of new technologies for autonomous health management of electrical power systems. Power system faults cover a wide range of problems, some of which is covered under power electronics faults and wiring chafing sections of this study. The main focus of this section is technologies developed for arc prevention and power management.

The arcing of electrical-powered systems is a major safety concern to both new and legacy aircraft. The advent of high-voltage direct current systems accentuates this problem. Arc fault prevention methods and algorithms address this critical need for electrical power system health management. Arcing faults occur as a result of chafing and cracking of insulation, dielectric breakdown, and looseness at terminal connections. Once arcing is initiated, damage may propagate to other conductors in the wire bundle. The discharge of arcing energy results in insulation damage, smoke events, the loss of adjacent wires in a wire bundle, and ignition of flammable materials and vapors. The use of thermal circuit breakers is a common technique used for arc fault prevention. An arc fault circuit interrupter is a new technology developed for arc prevention (Ref. 61) that relies on arc fault circuit breakers as a supplemental protection against arc fault conditions and thermal overload. Current circuit breakers only provide for thermal overload protection. Solid-state devices are also proposed as a potential replacement for traditional thermal circuit breakers for arc fault prevention. These devices typically have longer life-cycle, faster response time for overloads, and lower power dissipation when compared to current circuit breakers (Ref. 62).

Technologies have been developed for management of digital power distribution and arc fault management. An example is the Aircraft Electrical Power Systems Prognostics and Health Management Program (Ref. 63) sponsored by the Air Force Research Laboratory. The architecture developed in this program enables the digital data to provide component operating signatures to the system, thereby facilitating advanced diagnostic and prognostic capabilities. Other arc fault management systems can monitor the operation of the loads. Examples include marker lights to flag failures, motors and actuators for acceptable current levels, and operations of loads for time and duration (Ref. 62). A distributed power system is another new technology that is an alternative to traditional centralized power systems. It is based on locating the power control devices near the electrical loads to reduce the amount of power wiring. The control commands for this type configuration are sent to the power control devices with a data bus. Use of a distributed power distribution unit not only significantly reduces wire weight, but can lower installation and maintenance costs just based on the reduction in the number of connections.

11. Control surface faults (aileron, rudder, or elevator)

There is quite a lot of technology currently in use in the area of control surface faults. Frequently, the faults associated with control surfaces come about because of problems with the actuators or hydraulic systems that move the control surfaces and keep them in position. Excessive loads can also cause structural damage including cracks and fractures. The presence of one of these faults can mean that the control surface gets stuck at a certain trim, is more difficult to position, or becomes completely ineffective. Algorithms have been developed that use flight variables to detect these types of faults (Ref. 64). Once a fault is detected, flight control software can diagnose the problem by identifying the specific faulty component. Some systems have been designed that give this information to the pilot. More advanced algorithms have been developed that estimate the performance degradation and new flight envelope in the presence of the failure. Additional research focuses on the performance of autoland systems in the presence of a control surface fault. Because of the precision needed at landing, this phase of flight is particularly susceptible to loss of control due to control surface faults (Ref. 65). Numerous groups have designed flight control software packages that incorporate neural networks for additional capabilities to be used in landing with control surface faults.

12. Instrumentation, communication, and navigation failures

One common problem related to instrumentation, communication, and navigation faults is that these faults are often noticed by the flight crew, but not by detection systems (Ref. 66). Current detection methods are similar to those of wire chafing, in which impedance is measured for various electronics, and variations from the norm are detected as faults. Often faults are not detected because the variation in impedance is too small. Pulse-arrested spark discharge is one promising fault detection method that can be used to detect electronics faults that cannot be detected using impedance methods (Ref. 67). Onboard navigation faults are becoming less relevant due to the increased use of the global positioning system (GPS), because it uses data transmitted via satellites as opposed to electronics integrated with the rest of the aircraft, although the use of GPS could introduce a new set of faults. Similarly, utilization of wireless networks onboard aircraft could reduce the reliance on physical wiring in the future, eliminating many of the current failure modes (Ref. 58).

13. Fuel system faults

The majority of fuel system faults occur because of water condensation. This condensation can be especially harmful in freezing temperatures causing degraded performance and clogged filters. There are very few diagnostic systems specifically for fuel systems and even fewer systems that can mitigate detected faults. The conventional method of fuel system management is via a central computer system that controls fuel distribution among various tanks according to the stage of flight. Researchers at Penn State University have developed an adaptive fuel filtering system with parallel pumps. Data is collected via pressure sensors and can be used to identify faults or clogged filters. Integrated logic can adjust the flow or use water from the water separator to back flush clogged filters. A successful integrated test of this system was performed using a test rig constructed with diesel engines (Ref. 68). Multiple groups are researching alternatives to the use of the central computer systems for fuel management that use distributed networks of sensors and microcontrollers. The microcontrollers are used to control the fuel pumps using input from the sensor network to achieve the desired distribution of fuel in the tanks. This network of smart sensors eliminates the need for a central computer (Ref. 69). One method of decreasing fire risk in the fuel tanks is to replace electromechanical sensors, which have a higher risk of initiating combustion in flammable environments, with fiber optic sensors (Ref. 70). Another technology to decrease fuel-system-related fires involves detection of electrical faults in the fuel pumps. A retrofit device called a universal fault interrupter was approved for use on some aircraft in 2008. It is an electrical box that is installed adjacent to the electrical relay. It can detect electrical faults in the fuel pump, and it shuts down the pump when the inlet is uncovered or in times of uncommanded pump operation (Ref. 71).

14. Engine stall and/or faults in turbomachinery

Technologies developed to monitor and prevent engine stall and faults in turbomachinery cover a wide variety of techniques. These include monitoring of specific vibrations in an individual blade to prevent the potential of catastrophic failure and prevent turbine downtime. Specific technologies for blade vibration monitoring include eddy current, optical, and capacitive sensors as well as algorithms that can process and fuse data from these sensors. Eddy current sensors are used for the purpose of gas turbine engine stability monitoring including stall detection and blade harmonics (Ref. 19). Microwave blade tip sensors have considerable promise as a state awareness technique for the monitoring of rotating blades and disks (Refs. 72 and 73). These sensors produce information-rich waveforms of the blade-end geometry. Foreign object damage (FOD) detection systems comprise a suite of new technologies. These include systems for detecting and analyzing ultrasound or stress waves emitted when an object enters the intake of a turbine engine and impacts one or more of the blades in the engine. Upon detection, the FOD detection system can immediately inform the operator, inform another electronic device (computer, etc.), and/or latch the event for review by maintenance personnel (Ref. 23).

Debris monitoring is another technology applicable to engine health monitoring (Ref. 74). The fundamental principle of gas path debris monitoring is to sense the electrostatic charge associated with debris present in the gas path of jet engines or gas turbines. The engine distress monitoring system and the

ingested debris monitoring system are two technologies demonstrated on the United States' Joint Strike Fighter Pro Seeded Fault Engine Test program. Tomography is another technology based on hyperspectral absorption spectroscopy for temporally and spatially resolved temperature and water concentration measurements in practical combustion devices.

Surface acoustic wave sensors are another technology with demonstrated application to turbine engines (Ref. 75). These sensors can be used as multifunctional temperature and pressure sensing devices for turbine engine test validation. Finally, developing harsh environment sensors is also critical to engine health management. Notable technologies in this class include silicon carbide sensor devices that can work at high temperatures up to 500 °C that can be used for sensing motion, acceleration and gas flow, gas composition, and radiation detection. Another harsh environment sensor development for propulsion system applications is ceramic sensors that are not limited thermally when compared to traditional metal thin film sensors.

15. Landing gear faults

The current methods used by commercial airlines for landing gear health management mostly relate to routine maintenance and visual inspections. Additional maintenance may also be performed based on flight data or pilot observations. For example, a perceived hard landing by the pilot might warrant some extra maintenance procedures. Unfortunately, some operational scenarios that put larger than normal loads on the landing gear may not be reported if the pilot does not think of the scenario as a hard landing. Research is being conducted to design a load sensor to be able to monitor this information (Ref. 76). Currently, structural sensors are not integrated into any landing gear systems. Even if a scenario causes some sort of damage to the structure, and it does get reported, it is possible that a visual inspection will not find the problem. For example, some stress fractures to the structure may not be visible without disassembling the main gear. Acoustic emission is a technique being developed that could detect faults in structures and breakage of seals (Ref. 30). During inspection, the technician uses a device to propagate acoustic waves. Sensors pick up potential variations in the waves caused by faults (Ref. 77). Another area of concern in landing gear is shimmy during taxiing and landing. Shimmy is an oscillation of the structure that is normally caused by rough runways, usually around 10 to 30 Hz. Although shimmy does not usually cause catastrophic failures, it can cause excessive wear over time. A current method for dealing with shimmy is physical dampers that cannot adapt to changing situations. A new adaptive model uses sensors to detect shimmy, calculates the taxiing velocity and yaw angle to minimize the shimmy, and gives this information to the pilot (Ref. 78). Currently, no production aircraft have this technology.

16. Brake and/or anti-skid system faults

Conventional anti-skid systems consist of sensors that are used to detect when wheels lock, directing the brakes to pulse. Better algorithms in the anti-skid system control unit could help decrease skids and stopping distance and increase reliability. Research is being conducted to improve algorithms for use in anti-skid controllers (Ref. 79). There are also units that are designed to detect potential faults in the braking system. By utilizing braking data, an anti-skid control unit produced by General Atomics has the capability to detect anomalies in actual braking performance in contrast to expected performance. These anomalies act as a red flag for potential faults in the system (Ref. 80). Although this assists in the detection of potential failures, there is very little research addressing detection of the early stages of failure. The products on the market, such as the controller from General Atomics, are backward-looking, and the mitigation is based on maintenance. Some research is being conducted in a brake-monitoring system that will offer some prognostic capabilities. This system involves using sensors to monitor wear on friction surfaces and pressure sensors to monitor conditions in hydraulics. As anomalies from normal sensor data become apparent, the system reports to a user interface that the risk of failure is high for a specific component (Ref. 81). Although this technology does not include fault mitigation, it can help increase operator awareness of conditions and decrease costs by reducing the need for frequent routine maintenance.

17. Lightning- and radiation-related avionics faults

There is not a great deal of research in the area of lightning- and radiation-related avionics faults, but there are some models that show the electrical and thermal effects on the airframe after a lightning strike occurs. For example, if a lightning strike hits the nose of an airplane, models predict the intensity and time progression of voltage and thermal effects across the airframe. This prediction might be used to estimate the probability that avionics are damaged. The worldwide distribution of lightning strikes can be detected using satellite data, and this technology is used to alert aircraft operators when and where high lightning concentrations will be present. Lightning damage to metallic aircraft structures is not a problem; however, composites are being increasingly used in modern aircraft. Composite materials do not conduct and dissipate electricity. Lightning strikes could cause metal control cables to vaporize, metal hinges to weld, and vapors within fuel tanks to explode. A number of lightning strike protection materials have been developed (Ref. 82). Improved methods are needed for the detection of lightning strikes to composite materials as well as ways of diagnosing the impacts of the lightning strikes (Ref. 83).

Summary

A previous study conducted under the NASA Integrated Vehicle Health Management (IVHM) Project identified example damage conditions related to a set of adverse event fault types. One of the products of this previous study was Table 1 that identified 17 example damage conditions spanning across the five different adverse event fault types. The current study serves as a survey of the state of the art in IVHM technologies that relate to the 17 example damage conditions. As the scope of this study would make an in depth discussion of each technology infeasible, readers are encouraged to examine the references for more detailed information on the technologies summarized in the various sections.

As a result of this survey, we have found that certain gaps still exist that create barriers for effective development and deployment of integrated health management technologies that address the documented example damage conditions. These are summarized below.

System-level perspective.—A large obstacle to the development of IVHM technologies is the lack of a system-level perspective. This is often encountered with technology development efforts devoted to detection of a specific phenomenon or diagnostics and prognostics of a particular subsystem. Researchers usually develop technologies that successfully meet the requirements at the subsystem level, but fail to meet the verification and validation at the system level.

Systems integration.—Systems integration presents a big technical challenge. Most technologies are developed and matured only to a certain level without being effectively tested and integrated within the broader system. Our results show that, although promising, most of the IVHM technologies reported in this survey are yet to be integrated into a flight system.

Mitigation challenges.—IVHM technologies that fall under the mitigation theme often are yet to fully benefit from automation. In most subsystems and example damage condition domains, mitigation technologies lag behind detection, diagnosis, and prognosis. One reason for this deficiency is the fact that the decision systems employing mitigation strategies are typically not directly considered during the development of diagnostics and prognostic systems; however, the mitigation strategies are direct users of the information that is generated by such systems.

Flight safety.—Not all of the example damage conditions documented in the adverse events table have the same level of maturity when it comes to the technologies developed to address them. This has implications for flight safety. Damage conditions such as “icing conditions in propulsion systems,” “lightning-related avionic faults,” “delamination in composites,” and “fault of power

electronics” still demand a better understanding of the physical phenomenon that cause faulty behavior in flight systems. Models and methods that would facilitate the detection, diagnosis, prognosis, and mitigation of these damage conditions during flight are yet to mature to levels demonstrated by technologies in other domains.

Appendix A.—Acronyms

ASRS	Aviation Safety Reporting System
AvSafe	Agency's Aviation Safety Program
ECI	eddy current inspection
EMA	electromechanical actuator
FAA	Federal Aviation Administration
FOD	foreign object damage
GE	General Electric
GPS	global positioning system
IVHM	Integrated Vehicle Health Management
NDI	nondestructive inspection
NTSB	National Transportation Safety Board
PZT	piezoelectric transducer
RLI	robust laser interferometer
RUL	remaining useful life
TDR	time domain reflectometry

References

1. Srivastava, Ashok N.; Mah, Robert W.; and Meyer, Claudia: Integrated Vehicle Health Management. NASA Technical Plan, version 2.03, 2008.
http://www.aeronautics.nasa.gov/nra_pdf/ivhm_tech_plan_c1.pdf. Accessed July 20, 2009.
2. Reveley, Mary, et al.: Causal Factors and Adverse Conditions of Aviation Accident and Incidents Related to Integrated Vehicle Health Management. NASA/TM—2011-216967 (to be published).
3. Jones, Sharon Monica, et al.: Subsonic Aircraft Safety Icing Study. NASA/TM—2008-215107, 2008.
4. McDonough, Frank, et al.: The Forecast Icing Potential Algorithm. AIAA—2004—231, 2004.
<http://ams.confex.com/ams/pdfpapers/70666.pdf> Accessed August 14, 2009.
5. Reehorst, Andrew L.; and Koeing, George G.: Preliminary Analysis of X-Band and Ka-Band Radar for Use in the Detection of Icing Conditions Aloft. NASA/TM—2004-212901 (AIAA—2004—0233), 2004. <http://gltrs.grc.nasa.gov/reports/2004/TM-2004-212901.pdf> Accessed August 14, 2009.
6. Bassey, Christopher E.; and Simpson, Gregory R.: Aircraft Ice Detection using Time Domain Reflectometry with Coplanar Sensors. IEEEAC paper 1289, 2007.
7. Das, Kaushik; and Hamed, Awatef: Ice Shape Prediction for Turbofan Rotating Blades. AIAA—2006—209, 2006.
8. Domingos, Rodrigo Hoffmann, et al.: Development of an Engine Anti-Ice Protection System Using Experimental and Numerical Approaches. SAE 2007—01—3355, 2007.
9. Mason, Jeanne: 747 CF6—80C2 Icing Events. Boeing Commercial Airplanes Presentation, 2004.
http://www.smartcockpit.com/data/pdfs/plane/boeing/B747/instructor/B747_CF-6-80C2_Icing.pdf Accessed August 14, 2009.
10. Vichare, Nikhil M.; and Pecht, Michael G.: Prognostics and Health Management of Electronics. IEEE Trans. Compon. Packag. Technol., vol. 29, no. 1, 2006, pp. 222—229.
11. Bagul, Yogesh G.; Zeid, Ibrahim; and Kamarthi, Sagar V.: Overview of Remaining Useful Life Methodologies. Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., DETC2008—49938, 2008, pp. 1391—1400.
12. Przytula, K.W.; and Thompson, D.: Development of Bayesian Diagnostic Models Using Troubleshooting Flow Diagrams. Proc. SPIE Int. Soc. Opt. Eng., vol. 4389, 2001, pp. 110—120.
13. Lall, P., et al.: Prognostics and Health Management of Electronic Packaging. IEEE Trans. Compon. Packag. Technol., vol. 29, no. 3, 2006, pp. 666—677.
14. Simons, J.W.; and Shockey, D.A.: Prognostics Modeling of Solder Joints in Electronic Components. Proceedings of the 2006 IEEE Aerospace Conference, Big Sky, MT, 2006.
15. Baybutt, Mark, et al.: Prognostics and Health Management for Digital Electronic Boards. Proceedings of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, VA, 2007.
16. Bower, Gregory, et al.: SiC Power Electronics Packaging Prognostics. IEEEAC paper 1677, 2008.
17. Schneiker, Conrad, et al.: Advanced Electronic Prognostics for Integrated Circuits. Proceedings of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, VA, 2007.
18. Vohnout, Sonia, et al.: Electronic Prognostics System Implementation on Power Actuator Components. IEEEAC paper 1114, 2008.
19. Lane, Richard A.: Sensors and Sensing Technologies for Integrated Vehicle Health Monitoring Systems. AMPTIAC Quarterly, vol. 8, no. 3, 2004, pp. 11—15.
20. Karchnak, M.F.: A Robust Laser Interferometer (RLI) for Prognostics and Health Management (PHM). Proc. ASME Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., DETC2008—49421, 2008, pp. 1333—1345.
21. Goebel, K.; Bonanni, P.; and Eklund, N.: Towards an Integrated Reasoner for Bearings Prognostics. Proceedings of the 2005 IEEE Aerospace Conference, Big Sky, MT, 2005, pp. 3647—3657.
22. Marble, Sean; and Morton, Brogan P.: Predicting the Remaining Life of Propulsion System Bearings. IEEEAC paper 1350, 2006.

23. Hess Andrew: Joint Strike Fighter: An Overview of PHM Technology—30 Years of Perspective. Presented at the Propulsion Safety and Affordable Readiness Program Review/Joint Strike Fighter Program Office and NAVAIR 4.4. Jacksonville, FL, March 28–30, 2006.
24. Khalak, A.; Colman, Gregory D.; and Hess, Andrew J.: Damage Prediction for Interconnected, Degrading Systems. IEEEAC paper 1070, 2004, pp. 3507–3516.
25. Draney, Rodrick K.: High Temperature Sensor for Bearing Health Monitoring. IEEEAC paper 1165, 2004.
26. Neslen, Craig, et al.: Advanced Sensor Development for Propulsion Health Monitoring. Proceedings of the 2007 Conference of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, VA, 2007.
27. Neslen, Craig, et al.: Advanced Sensor Development for Propulsion Health Monitoring. Proceedings of the 2008 Conference of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, VA, 2008.
28. Wincheski, Russell A.: Development of Eddy Current Techniques for Detection of Deep Fatigue Cracks in Multi-Layer Airframe Components. Presented at the NASA Aviation Safety Technical Conference, Denver, CO, 2008.
29. Baker, Alan: Structural Health Monitoring of a Bonded Composite Patch Repair on a Fatigue-Cracked F-111C Wing. DSTO-RR-0335, 2008.
30. Banks, Jeffrey C.; Reichard, Karl M.; and Brought, Mark S.: Lubrication Level Diagnostics Using Vibration Analysis. Proceedings of the 2004 IEEE Aerospace Conference, vol. 6, 2004, pp. 3528–3534.
31. Akers, Douglas W.; Rideout, Curtis A.; and Ritchie, Scott J.: Nondestructive Aging and Cross-Link Density Damage Detection In Solid Rocket Fuel Propellant. AIAA-2005-4363, 2005.
32. Rideout, Curtis A.; and Ritchie, Scott J.: New Techniques for Detecting Early Fatigue Damage Accumulation in Aircraft Structural Components. IEEEAC paper 1244, 2007.
33. Starnes, James H., et al.: Advances in Structural Integrity Analysis Methods for Aging Metallic Airframe Structures with Local Damage. RTO-MP-079(II), 2003, pp. 27-1 to 27-16.
34. Farley, Gary L.; Newman, John A.; and James, Mark A.: Selective Reinforcement to Improve Fracture Toughness and Fatigue Crack Growth Resistance in Metallic Structures. AIAA 2004-1924, 2004.
35. Rodrigues, Elenice Maria, et al.: Fatigue Crack Growth Resistance and Crack Closure Behavior in Two Aluminum Alloys for Aeronautical Applications. Mater. Res., vol. 8, no. 3, 2005, pp. 287–291.
36. Schijve, Jaap: Fatigue Damage in Aircraft Structures, Not Wanted, But Tolerated? Int. J. Fatigue, vol. 31, no. 6, 2009, pp. 998–1011.
37. Chang, Fu-Kuo, et al.: Design of SHM-Embedded Structures for Space Operation Vehicles. Proceedings of the 2005 Integrated System Health Engineering and Management (ISHEM). NASA Intelligent Systems Division at Ames Research Center, 2005.
http://ti.arc.nasa.gov/projects/ishem/Papers/Chang_Structures.doc Accessed November 5, 2010.
38. Yashiro, S., et al.: A New Approach To Predicting Multiple Damage States in Composite Laminates With Embedded FBG Sensors. Compos. Sci. Technol., vol. 65, nos. 3–4, 2005, pp. 659–667.
39. Krishnaswamy, Sridhar: Structural Health Monitoring for Life Management of Aircraft. Presented at the FAA JAMS 2008 Technical Review Meeting, Everett, WA, 2008.
40. Elder, David J., et al.: Review of Delamination Predictive Methods for Low Speed Impact of Composite Laminates. Compos. Struct., vol. 66, nos. 1–4, 2004, pp. 677–683.
41. Roemer, Michael J., et al.: Autonomous Impact Damage Detection and Isolation Prediction for Aerospace Structures. IEEEAC paper 1341, 2005, pp. 3592–3600.
42. Das, K.; Hamed, A.; and Basu, D.: Ice Shape Prediction for Turbofan Rotating Blades. AIAA-2006-209, 2006.
43. Lavretsky, Eugene; and Chidambaram, Bala: Health Monitoring of an Electro-Hydraulic System Using Ordered Neural Networks. Proceed. Int. Jt. Conf. Neural Networks, Honolulu, HI, 2002, pp. 2893–2898.

44. Succi, George P.; and Chin, Harrison: Helicopter Hydraulic Pump Condition Monitoring Using Neural Net Analysis of the Vibration Signature. Presented at the 1996 SAE Aerospace Atlantic Conference, paper no. 961307, 1996. http://www.appliedconceptresearch.com/SAE_961307.pdf Accessed November 5, 2010.
45. Angeli, Chrissanthi; and Chatzinikolaou, Avraam: On-Line Fault Detection and Compensation of Hydraulic Driven Machines Using Modelling Techniques. *JACIII*, vol. 12, no. 2, 2008, pp. 111–115.
46. Byington, Carl S., et al.: A Model-Based Approach to Prognostics and Health Management for Flight Control Actuators. *Proceedings of the 2004 IEEE Aerospace Conference*, vol. 6, 2004, pp. 3551–3562.
47. Falcou, Gerard, et al.: Compensated Actuator With Optimized Power. U.S. Patent 6,928,894 B2, Aug. 2005. http://www.patentstorm.us/inventors-patents/G%C3%A9rard_Falcou/4027666/1.html Accessed November 5, 2010.
48. Al-Garni, Ahmed, et al.: Reliability Analysis of Aircraft Air Conditioning Packs. *Aircraft Engineering Symposium*, Jeddah, Saudi Arabia, 2004.
49. Al-Garni, Ahmed Z., et al.: Failure Forecasting of Aircraft Air-Conditioning/Cooling Pack With Field Data. *J. Aircraft*, vol. 44, no. 3, 2007, pp. 996–1002.
50. Army Oil Analysis Program (AOAP). AMC Regulation 11–47, U.S. Army Materiel Command, Fort Belvoir, VA, 2006. <http://www.amc.army.mil/pa/pubs/AMC-R11-47.pdf> Accessed November 8, 2010.
51. Engine Oil Analysis: Used to Trigger Maintenance Action. *Aviation Today*, Sept. 1, 2006.
52. Slenski, George A.; and Michael F. Walz: Novel Technologies for Improving Wire System Integrity. Ninth Aging Aircraft Conference, Atlanta, GA, March 6–9, 2006, <http://www.electricity-tool.com/doc/120354-NOVEL-TECHNOLOGIES-FOR-IMPROVING-WIRE-SYSTEM-INTEGRITY/>.
53. Lectromec LECTROGRAM: June 2004 Newsletter, A Resource for Your Wire Maintenance Program. 2006. <http://www.wirefacts.com/AddDocs/Lectrogram%20-%20Issue%2011.pdf> Accessed November 8, 2010.
54. Wheeler, Kevin R., et al.: Health Management for Wire Insulator Integrity. NASA Ames Research Center, Moffett Field, CA, 2008. http://ti.arc.nasa.gov/m/pub/101/101_Wheeler.pdf Accessed November 8, 2010.
55. Smart Structures Technology for Transportation Safety. Innovative Dynamics Inc. <http://www.idiny.com/>
56. Kuhn, Paul K.; Furse, Cynthia; and Smith, Paul: Locating Hidden Hazards in Electrical Wiring. Presented at the Aged Electrical Systems Research Application Symposium, National Fire Protection Research Foundation, Quincy, MA, 2006.
57. Felton, B.: New Sensor Detects Wire Chafing. *INTECH*, vol. 49, no. 1, 2002.
58. Lebold, Mitchell S., et al.: Wireless Technology Study and the Use of Smart Sensors for Intelligent Control and Automation. *Proceedings of the 2005 IEEE Aerospace Conference*, Big Sky, MT, 2005.
59. Karchnak Martin; and Shipman, Robert: Opportunities for Prognostic Health Monitoring. *Proceedings of the 2007 IEEE Aerospace Conference*. Big Sky, MT, 2007.
60. Bechhoefer, Eric; and Yu, Jun: Algorithm Development to Ascertain the True Characteristic Impedance of a Wire for Wire Diagnostics. *IEEEAC paper 1104*, 2005, pp. 3797–3802.
61. Pellon, Christian V., et al.: Aircraft Electrical System Monitoring with Arc Fault Circuit Protection and Automatic Fault Location. *Proceedings of the 2006 Power Systems Conference*, SAE 2006–01–3091, 2006.
62. Potter, J.F.; and Furmanski D.: Retrofitting Solid State Power Distribution Into Existing Aircraft. 9th Joint FAA/DoD/NASA Aging Aircraft Conference, Atlanta, GA, March 6–9, 2006.
63. Keller, Kirby J.; Del Amo, Ana; and Jordan, Brett: Aircraft Electrical Power Systems Prognostics and Health Management (AEPHM). SAE 2004–01–3162, 2004.
64. Bateman, Francois; Noura, Hassan; and Ouladsine, Mustapha: Active Fault Detection and Isolation Strategy for an Unmanned Aerial Vehicle With Redundant Flight Control Surfaces. *Proceedings of*

- the 2008 Mediterranean Conference on Control and Automation, Ajaccio, France, 2008, pp. 1246–1251.
65. Naikal, Nikhil S., et al.: Improved Fault Tolerance for Autoland Using Adaptive Backstepping Neural Controller. Proceedings of the IEEE International Conference on Control Applications. Singapore, 2007, pp. 1203–1208.
 66. Burchell, Bill: Untangling No Fault Found. Aviation W., Feb. 9, 2007.
 67. Howard, Kevin: Finding a Short Circuit Before It Finds You. PHYSorg.com, Sandia National Laboratories, June 20, 2006. <http://www.physorg.com/news70015178.html> Accessed August 20, 2009.
 68. Murphy, Brian J., et al.: Diagnostic Fault Detection & Intelligent Reconfiguration of Fuel Delivery Systems. Proceedings of the 2005 IEEE Aerospace Conference, Big Sky, MT, 2005, pp. 3514–3522.
 69. Insaurralde, Carlos C., et al.: Experimental Results With a New Distributed Aircraft Fuel Control System Which Uses Smart Fieldbus Components. Proceedings of the 2006 IEEE/AIAA 25th Digital Avionics Systems Conference, Portland, OR, 2006.
 70. Barroqueiro, S.; and Jones, G.R.: Chromatic Single Point Sensor for Aircraft Fuel Systems. Meas. Sci. Technol., vol. 15, no. 5, 2004, pp. 814–820.
 71. TDG Aerospace's UFI(R) Electrical Fault Detection System is an Approved Means of Compliance With New FAA Airworthiness Directive AD2008–11–07. Reuters.com, May 30, 2008. <http://www.reuters.com/article/idUS114701+30-May-2008+PRN20080530> Accessed August 24, 2009.
 72. Holst, Thomas A., et al.: Development of an Optical-Electromagnetic Model of a Microwave Blade Tip Sensor. AIAA–2005–4377, 2005.
 73. Wang, Wenyi.: Disk Crack Detection and Diagnosis for Gas Turbine Engines. IEEEAC paper 1313, 2006.
 74. Powrie, Honor; and Novis, Ari: Gas Path Debris Monitoring for F–35 Joint Strike Fighter Propulsion System PHM. IEEEAC paper 1100, 2006.
 75. Hinders, Mark: Intelligent Structural Health Monitoring with Guided Ultrasonic Wave Sensors. Proceedings of the Society for Machinery Failure Prevention Technology (MFPT), Virginia Beach, VA, 2008.
 76. Yates, Michael Stuart; and Keen, Phillip: Landing Load Monitor for Aircraft Landing Gear. World Intellectual Property Organization Pub. No. WO/2007/023280, 2007.
 77. Geng, Rong S., et al.: Application of AE Technique onto Landing Gear Controlling Test of an Aircraft. Proceedings of the 9th European Conference on NDT, Berlin, Germany, 2006. <http://www.ndt.net/article/ecndt2006/doc/P8.pdf> Accessed November 8, 2010.
 78. Munns, Thomas; and Palmer, Matthew: Health Management Technologies and Experiments for Transport Aircraft Landing Gear. AIAA–2005–6355, 2005.
 79. Lee, Ki-Chang, et al.: Comparison between Software Simulation and HIL Simulation of Antiskid Brake System for Aircrafts. Proceedings of the 31st Annual Conference of the IEEE Industrial Electronics Society, 2005.
 80. General Atomics, “BACS: Brake Antiskid Control System.” Systems, Space & Materials Division—Aircraft Control, <http://www.ga.com/news.php?read=1&id=171&page=3>, Accessed August 20, 2009
 81. Murphy, Brian J., et al.: Diagnostic End to End Monitoring & Fault Detection for Braking Systems. Proceedings of the 2006 IEEE Aerospace Conference, Big Sky, MT, 2006.
 82. Gardiner, Ginger: Lightning Strike Protection For Composite Structures. High Performance, Composites World, July 2006. <http://www.compositesworld.com/articles/lightning-strike-protection-for-composite-structures> Accessed August 25, 2010.
 83. Szatkowski, George: Lightning Strike Protection for Composite Aircraft. NASA Tech Briefs, June 1, 2009. <http://www.techbriefs.com/component/content/article/5358>, Accessed August 25, 2010.

84. Hale, Justin: Boeing 787 from the Ground Up. Boeing QTR_04, 2006.
http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/AERO_Q406_article4.pdf
Accessed November 8, 2010.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-12-2010		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Assessment of the State of the Art of Integrated Vehicle Health Management Technologies as Applicable to Damage Conditions			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Reveley, Mary, S.; Kurtoglu, Tolga; Leone, Karen, M.; Briggs, Jeffrey, L.; Withrow, Colleen, A.			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER WBS 645846.02.07.03.16		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			8. PERFORMING ORGANIZATION REPORT NUMBER E-17487		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITOR'S ACRONYM(S) NASA		
			11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2010-216911		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Category: 03 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT A survey of literature from academia, industry, and other Government agencies assessed the state of the art in current integrated vehicle health management (IVHM) aircraft technologies. These are the technologies that are used for assessing vehicle health at the system and subsystem level. This study reports on how these technologies are employed by major military and commercial platforms for detection, diagnosis, prognosis, and mitigation. Over 200 papers from five conferences from the time period of 2004 to 2009 were reviewed. Over 30 of these IVHM technologies are then mapped into the 17 different adverse event damage conditions identified in a previous study. This study illustrates existing gaps and opportunities for additional research by the NASA IVHM Project.					
15. SUBJECT TERMS Flight safety; Aircraft safety					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 24	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			UU

