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Development and Flight Testing of an Adaptable Vehicle Health-Monitoring Architecture

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Development and testing of an adaptable vehicle health-monitoring architecture is presented. The architecture is being developed for a fleet of vehicles. It has three operational levels: one or more remote data acquisition units located throughout a vehicle, a command and control unit located within a vehicle, and a terminal collection unit to collect analysis results from all vehicles. Each level is capable of performing autonomous analysis with a trained expert system. The expert system is parameterized, which makes it adaptable to be trained to both a user's subjective reasoning and existing quantitative analytic tools. Communication between all levels is done with wireless radio frequency interfaces. The remote data acquisition unit has an eight-channel programmable digital interface that allows the user discretion for choosing type of sensors, number of sensors, sensor sampling rate, and sampling duration for each sensor. The architecture provides framework for a tributary analysis. All measurements at the lowest operational level are reduced to provide analysis results necessary to gauge changes from established baselines. These are then collected at the next level to identify any global trends or common features from the prior level. This process is repeated until the results are reduced at the highest operational level. In the framework, only analysis results are forwarded to the next level to reduce telemetry congestion. The system's remote data acquisition hardware and nonanalysis software have been flight tested on the NASA Langley Research Center's B757 main landing gear to validate the wireless radio frequency communication capabilities of the system, the hardware design, command and control, software operation, and, data acquisition, storage, and retrieval.

Introduction

EXISTING aircraft are often kept in service beyond their original design lives. As they age, they become susceptible to system malfunctions or fatigue. Unlike future aircraft designs that will have health-monitoring capabilities integrated into their designs, older aircraft have not been able to benefit from such technology. NASA Langley Research Center is developing and testing a health-monitoring hardware/software architecture designed to be retrofitted into an existing fleet of military and commercial aircraft, ships, or ground vehicles to provide them with state-of-the-art health-monitoring capabilities. The architecture is self-contained and requires limited integration intrusion into existing systems. In essence, it has bolt-on/bolt-off simplicity that makes it easy to implement on any existing vehicle or structure. Because the architecture is completely independent of the vehicle, it can be certified for airworthiness as an independent system. A detailed description of the architecture is given Ref. 1.

The objective of the health-monitoring system is to reduce vehicle operating costs, improve safety, and increase reliability. The architecture provides a means to identify vehicle subsystem degradation and/or damage before they become costly and/or disastrous. Frequent vehicle monitoring allows identification of the embryonic stages of damage or degradation. This knowledge can be used to correct the anomalies while still somewhat minor. Maintenance can be performed as needed instead of having the need for maintenance identified during cyclic inspections that take vehicles off duty even if there are no maintenance problems. Measurements and analyses acquired by the health-monitoring architecture can be used to analyze mishaps. By the identification of system problems before they become either costly or disastrous, vehicles can be more reliable and safer, while increasing their duty time.

In an *Aerospace America* commentary (January 2002), the former Federal Aviation Administration Administrator and former Secretary of the Air Force, John McLucas, suggested the need for an aircraft health-monitoring system. The system he described has all of the attributes of the NASA health-monitoring software and hardware architecture currently being developed and tested. The architecture provides a means to monitor vehicle and subsystem damage, degradation, usage, and the manner in which vehicle subsystems are maintained.

The system's remote data acquisition hardware and nonanalysis software have been flight tested on NASA Langley Boeing 757's most severe location to mount a health-monitoring device:

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the landing gear. Following the introduction will be an overview of the architecture, descriptions of the architecture's subsystems, and an expert system overview. Results from the airworthiness qualification tests (pressure, vibration, thermal, and electromagnetic interference testing) will be presented next. Hazard analysis will follow. A brief overview of the NASA Langley Research Center (LaRC) Boeing 757-200 airborne research integrated experiments system (ARIES) is then given. Flight-tests results are presented next. The next phase of the architecture development has already commenced. It includes installing autonomous capability for data reduction and analysis using the expert systems, with remote data aquisition units (RDAU) placed throughout the aircraft.

Architecture Overview

The architecture is a hardware and software infrastructure for health monitoring that can be easily developed to a health-monitoring system for a fleet of vehicles. It has three operational levels: one or more RDAUs located throughout a vehicle, a command and control unit (CCU) located within a vehicle, and a terminal collection unit (TCU) that is located at a fleet terminal, for example, an airfield. A schematic of the architecture is shown in Fig. 1. Programmable data acquisition circuitry and expert systems trained to performance baselines in each RDAU allow the architecture to be adaptable for many types of vehicles and structures. The programmable data acquisition circuitry allows type of sensor, sampling rate, and number sensors used to be at the discretion of the user. Wireless radio frequency transceivers are used to communicate with all of the architecture components.[1]

The architecture is capable of performing tributary analyses. Each operational level of the architecture has analysis capabilities with a user-trained expert system. Measurements collected at the lowest level are analyzed at that level. Analysis results are forwarded to a higher level, and all results are analyzed to ascertain global trends or anomalies for the prior level. This is repeated until all analyses are combined at the highest level. Figure 1 shows the architecture for multiple vehicles. The lowest level consists of one or more RDAUs in each vehicle capable of collecting and analyzing data using multiple data acquisition channels. The RDAU can perform analysis on measurements from each channel individually or from all channels fused together. The second level is a CCU that is capable of performing vehicle-level analysis. The CCU controls all communications from and to each RDAU. RDAU analysis results are forwarded to the CCU to perform similar analysis but for all RDAUs (that is, the vehicle big picture). At this level, global anomalies to the vehicle can be detected. The fused analysis can also be used to locate anomalies by triangulation or to identify spatial trends. After the end of flight, a vehicle's CCU analysis is forwarded to a TCU at the airfield. The TCU functions as a repository of all vehicles analyses and performs analyses using results forwarded from all vehicles. Here all vehicles can be compared to ascertain if there are common anomalies, for example, vendor-supplied bad brake pads, improperly manufactured linkages, etc.[1] The TCU also forwards analyses and data from the CCUs to keys users, such as maintenance personnel, airline operations, and manufacturers of vehicle subsystems. The architecture could also be used for a subsystem with multiple components, such as a landing gear system.

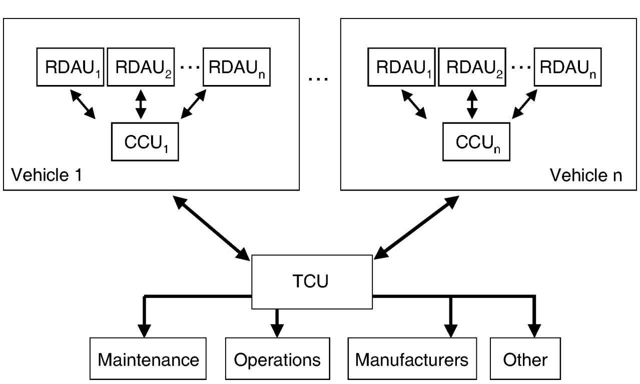


Fig. 1 Operational and analysis levels of the adaptable vehicle health-monitoring architecture.

Having adaptive expert systems at each analysis level eliminates the need for transmitting and storing large volumes of collected measurements. An expert system develops analysis results that are transmitted to the higher system levels. The expert system's key analytic tool is fuzzy logic for inference based on subjective reasoning and quantitative analysis. Fuzzy logic is used to emulate predicate reasoning, that is, if A then B, for many combinations of inputs that are used to form a decision. Fuzzy logic can also emulate human qualitative reasoning with the capability of incorporating multiple qualitative objectives.[2] When pattern recognition is required, a neural network can augment the expert system. A neural network is a computational structure that emulates rudimentary biological neural processing.

Subsystem Description

The three subsystems of the health-monitoring architecture are the RDAU, CCU, and TCU. The details of each subsystem will be presented in this section.

RDAU

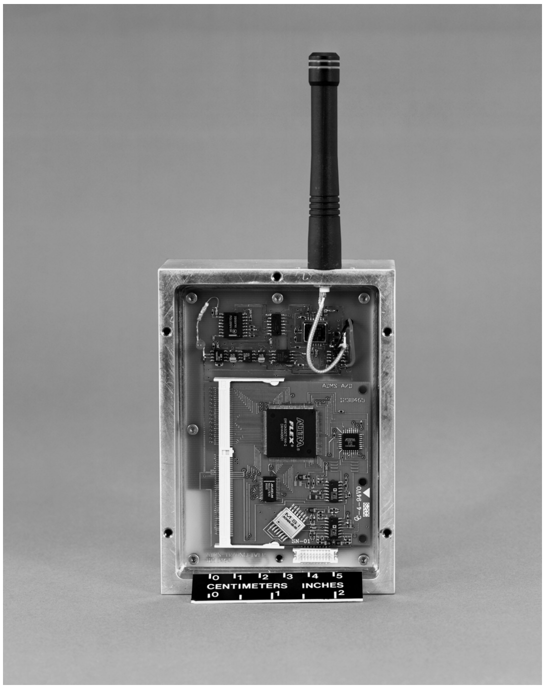
RDAUs are multisensor interfaces with an onboard miniature computer, microcontroller, programmable digital interface, nonvolatile solid-state memory, and wireless transceiver.[1] The RDAU electronics and housing are shown in Fig. 2. The onboard computer uses a disk operating system and performs data acquisition, data storage, and file management. The microcontroller regulates the tranceiver and instructs the computer to turn on when the power-on command is received from the CCU. The software embedded in the RDAU provides transceiver control, power management, encoder/decoder control, data acquisition, data storage, and file management. The autonomous analysis capability is currently being added to the architecture. Sensor data are acquired via a flexible sampling scheme through a programmable digital interface. A RDAU can accommodate eight sensor measurements. Five AA lithium batteries are used to supply power to each RDAU, or optional external power sources can be used. The housing and the mounting of internal electronics are designed to withstand impact during aircraft landing while mounted on the main landing gear. It is also designed to operate in nonenvironmentally controlled locations of the plane in temperatures of −50 to 55°C and pressure equivalent to 50,000-ft (15,239 m) altitude.

Any combination or type of sensors can easily be installed within the RDAU housing or external to the RDAU, for example, connected with wires or flex circuits. Each RDAU can sense numerous physical attributes, for example, sound, heat, or mechanical disturbance, within vicinity of an RDAU. Table 1 lists measurements of each channel during the flight tests.

Data acquisition circuitry is implemented in a single complex programmable logic device (CPLD) that can be reconfigured in-circuit, similar to a field programmable gate array (FPGA). The circuitry controls all analog-to-digital conversion. A first-in/first-out sample buffer and the buffer status are regulated by the circuitry. Time-division multiplexed sampling is used to provide multiple sampling rates for the individual channels within a prescribed sampling period. When sensors are measuring physical properties with different rates of change, the multiple sampling rates eliminates excessive sampling of a property that changes at a slower rate.[1]

Table 1 Remote data acquisition channel allocation

Channel	Measurement
1	Acceleration along roll axis
2	Acceleration along pitch axes
3	Acceleration along yaw axis
4	Sound, dB
5	RDAU temperature
6	Battery voltage
7	Spare
8	Reference



a) RDAU electronics

b) RDAU housing

Fig. 2 RDAU.

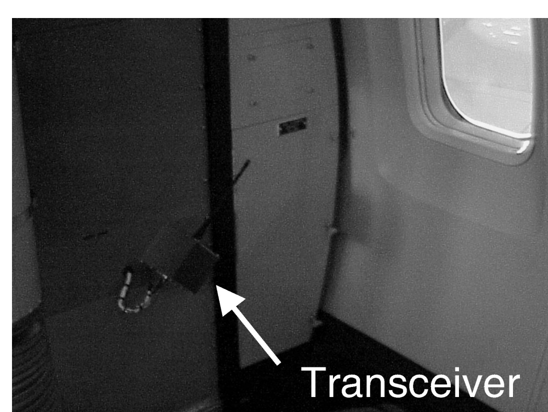
A transceiver operating at 433-MHz was used for communication with the CCU. The transceiver used 1-mW of power and amplitude shift keying modulation (somewhat similar to amplitude modulation). The 433-MHz frequency does not electromagnetically interfere with civilian aircraft communication and navigation systems. The microcontroller runs the RDAU power management algorithm. The algorithm continuously regulates the RDAU transceiver to power-off for 2 s, then power-on for 2 ms to acquire any commands broadcasted from the CCU. It then returns to power-off for 2 s if no commands are broadcasted. The algorithm continuously cycles the transceiver power in the aforementioned fashion. If there are broadcasted commands, the microcontroller commands the onboard miniature computer to power-on and to execute all commands contained in the CCU broadcast. The transceiver remains on until the commands are completed. Each RDAU has an addressable encoder/decoder through which commands can be received directly. RDAU status and data are received through serialized packet format.[1]

Once a suite of sensors is chosen for each RDAU and located on the vehicle, a baseline of acceptable vehicle performance is established from measurements acquired when the vehicle is performing correctly. Each RDAU uses an embedded expert system trained to its respective baseline. In nominal operation, each physical attribute sensed by a sensor interfaced to a RDAU has a performance envelope or established pattern that is indicative of the system (vehicle or plant) being and/or functioning within acceptable limits. Examples of these are measured landing gear loads during impact not being exceeded, brake noise frequency spectral content within established range, no major changes to structural frequencies that can be sense by a RDAU, or no anomalies in audio or vibration signatures. Measured profiles that show alterations to the signatures infer the system has changed.

CCU

The CCU regulates the health-monitoring activities on a vehicle.[1] The CCU is a computer-based subsystem that controls communications to and from all RDAUs (Fig. 1), regulates all RDAU measurement collection and analyses, and retrieves all RDAU collected data and analyses. It has the ability, using user-trained expert systems, to perform vehicle-level analysis of all RDAU analysis results. An example would be multiple RDAUs indicate a vibration anomaly. By the comparison of the relative amplitudes of the vibration anomaly and with the knowledge of the RDAUs relative locations, the CCU could triangulate on the location of the anomaly. Another example would be that analyses for all RDAUs could be used by the CCU to determine if there are any spatial trends to the anomalies. The CCU is shown in Fig. 3a. Figure 3b shows the transceiver for the CCU. A

a)



b)

Fig. 3 CCU: a) CCU mounted on NASA LaRC Boeing 757 experiment pallet, b) CCU transceiver mounted at rear of experiment pallet.

disk operating system is used in the CCU. The CCU can also serve as a power management tool by regulating when individual or combinations of RDAUs are powered-on. Communication, for RDAU control, is provided via a wireless radio frequency transceiver interface. The CCU can be manually controlled and reconfigured via common computer interfaces, for example, standard serial cable to a portable personal computer such as a laptop, personal digital assistant, or keypad. A user interface is provided to allow the user to control functions for a selected RDAU.

TCU

The TCU provides the means to autonomously retrieve vehicle analysis results from all vehicles CCUs.[1] The TCU performs analysis on all results collected from all vehicles to identify any fleet-wide anomalies, for example, all aircraft have the same faulty bearing at a similar location. The TCU is used to develop the final summary of the vehicle health results that get routed to the appropriate users, for example, maintenance workers, airlines operations, etc. A portable system that contains the nonanalysis capabilities of the TCU has been successfully demonstrated to download data after flights. The TCU is embodied as a Linux-based processor with radio frequency communication, Internet connectivity, expert systems, and installed software similar to that installed on the CCU. The TCU will constantly transmit a power-on command while awaiting the arrival of vehicles to within range of its transceiver. This command is repeated until there is a vehicle with a CCU in vicinity. When a vehicle is in vicinity, its CCU will be powered-on, and then all collected analysis will be transmitted. All newly collected results are then compared to those of other vehicles that have been collected. Any fleet-wide anomalies are then automatically reported to appropriate users via operating system commands that query the appropriate directories for new analysis reports and then to forward reports via emails or file transfer protocols.

Expert System Overview

Expert systems will be implemented in all operational levels of the health-monitoring architecture to facilitate autonomous analysis. They will also provide decision logic for the CCU, for example, for regulating RDAUs. The expert systems will be developed from tuned fuzzy mapping algorithms. The expert systems will allow subjective reasoning to be applied to all results (or measurements) in addition to quantitative analysis. When pattern recognition is required for the expert systems, neural networks can be used. Fuzzy logic mapping algorithms and neural networks are used because they are computationally efficient. A detailed description is provided in Ref. 2 of the development of the fuzzy expert system that is similar to what is to be implemented in this health-monitoring architecture. Fuzzy logic is used to emulate predicate reasoning, that is, if A then B, for many combinations of inputs that are used to form a decision. Fuzzy logic can also emulate human qualitative reasoning with the capability of incorporating multiple qualitative objectives. Conceptually, a fuzzy expert system is similar to that of a decision-logic architecture using a collection of binary if–then rules. The advantage of using fuzzy logic expert systems is that they can interpolate or extrapolate with fewer rules than the traditional binary expert systems. They have been shown to produce very good results in cases where the mathematical description of the system being controlled or analyzed may not be readily available, the description may be of questionable fidelity, or the inputs are imprecise.

A fuzzy expert system development algorithm has been developed at NASA LaRC that will allow users to develop a fuzzy expert system without having to be knowledgeable in fuzzy logic. The development algorithm is optimization based and only requires that users define their subjective reasoning into a set of decision rules of the form, if A and if B . . . then C. The user also supplies examples of metrics for those rules. Nested in the expert system development algorithm is a fuzzy mapping algorithm that dynamically sizes its working matrices to accommodate the user-supplied rules. The mapping algorithm is capable of determining permutations of all rules executed based on current inputs. The development algorithm uses the number of fuzzy membership sets in the collection of decision rules to develop an optimization design vector. The user-supplied metrics are used to tune the expert system via an optimization strategy. The optimization design objective is to minimize the error between the user-supplied output metrics and the outputs the mapping algorithm creates for the same set of inputs. The design vector is varied using methods such as gradient or genetic algorithms. The fuzzy expert system is tuned when a design vector is developed such that, when implemented in the fuzzy mapping algorithm, the mapping algorithm's output approximates those of the user for a given set of inputs. Before the development algorithm, making a fuzzy expert system required the user to formulate membership functions for various fuzzy sets, develop rules that map input conditions to decisions using fuzzy sets, and select fuzzification and defuzzification techniques for a small number of options.

The RDAU expert system will be trained using measurements collected when the vehicle is operating within specifications to establish a baseline. The user defines the significance, for example, how good or bad the subsystem is, of new measurements that are acquired that are not within established envelopes of the baselines. This gives the architecture the ability to analyze autonomously measurements to ascertain the health of the vehicle. The expert systems for the CCU and the TCU will be developed in a similar fashion.

Airworthiness Qualification Testing

Preflight qualification tests were performed to validate the airworthiness of the RDAU. The tests were performed to verify the operation of all electrical components, software, and radio frequency communication. Thermal cycling, pressure, vibration, and electromagnetic interference tests were performed. The integrity of the mechanical design, which included housing, and the mounting of electrical components was partially verified during vibration testing. The airworthiness qualification tests were performed in accordance with Ref. 3. The complete validation of the design was the objective of the flight tests.

Thermal Testing

The RDAU was operated at various temperatures to verify its ability to function at those temperatures. The RDAU was placed in a Tenney Jr. temperature chamber for 8 continuous hours. Figure 4 shows the temperature profile prescribed for the preflight qualification test, the actual temperature profile during the test, and results of temperature testing before the qualifying test. During qualification, there were four periods at which the temperature was held constant. The temperature rate of change between the holding periods was approximately 2.5°C/min. Temperature variation for flight qualification was from 20 to −40°C to 55 to 20°C. During preliminary testing the temperature varied from 20 to −50 to 20°C. The temperature was maintained at −50°C for 5 1/2 h.

RDAU and CCU operations were verified during testing. The RDAU power management algorithm ran continuously during

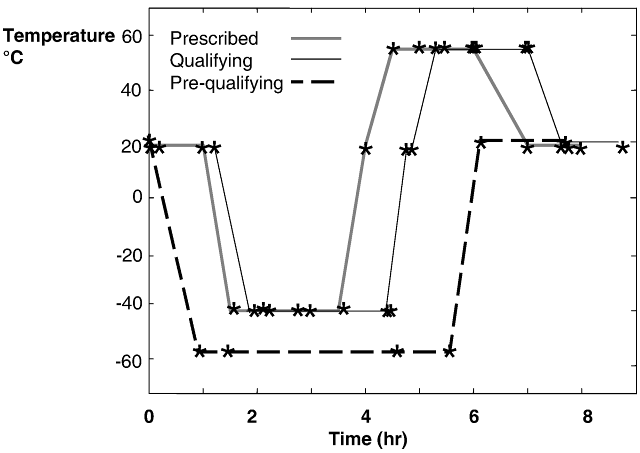


Fig. 4 Temperature profile used for thermal cycling RDAU; *, times of verification of CCU and the RDAU operations.

testing. Verification points are annotated on Fig. 4. At each verification time, the CCU transmitted a power-on command to the RDAU. The power-on command instructed the microcontroller (which runs the power management algorithm) to turn the RDAU computer on. The CCU then transmitted an acquire command to instruct the RDAU to acquire measurements for all eight channels. Following the acquire command, the CCU transmitted a download command to instruct the RDAU to transmit data packets to the CCU, while the CCU received and stored the packets. A power-off command was then sent to the RDAU to place the RDAU in a sleep mode. In the sleep mode, the computer used to control data acquisition and data storage was powered-off, and the microcontroller that controls the transceivers initiates the power management algorithm. The data received and stored by the CCU was then examined manually to verify that the correct pre-selected count (for reference channel) and the correct number of bytes for other the channels were received. The time and temperature of the oven was recorded at different intervals. The RDAU functioned correctly at all measurement points for all tests.

Altitude Testing

To qualify the RDAU for pressure conditions at 50,000 ft, the RDAU was placed in a Process Equipment Company vacuum chamber with the chamber pressure decreased to and stabilized at 87.0-mm hg (pressure at 50,000 ft for standard day). The test was initiated with the chamber temperature at ambient temperature and the RDAU positioned in the chamber so that it could be viewed through the front window of the chamber. Because the RDAU was battery operated with a radio frequency transceiver, no wiring connections were necessary. A radio frequency spectrum analyzer was used to verify that communications signals were either sent by the CCU or by the RDAU. During testing, the CCU was external to the vacuum chamber. The RDAU was tested before the altitude test to assure that it was working properly. Transceiver communication between the CCU and RDAU was verified before start of test with the pressure chamber door closed.

The chamber pressure was decreased to 87.0-mm hg and maintained at that pressure for 2 h. The RDAU performance was monitored during the 2 h by acquiring measurements from all channels every 30 min in same manner in which RDAU operation was verified during thermal testing. No malfunctions were observed for either the CCU or the RDAU during the altitude test. The operation of the RDAU was again verified after the vacuum chamber pressure was increased to ambient and the chamber was opened.

Vibration Testing

To verify that the RDAU could operate when subjected to vibration representative of what commercial transports could experience, the RDAU was subjected to vibration tests. A T1000 Unholtz–Dickie vibration table (Fig. 5), was used to provide the desired vibration. The RDAU was subjected to the two sinusoidal vibration spectrums shown in Figs. 6 and 7 for each orthogonal axes shown in Fig. 5. Both sine-sweep tests were conducted in each axis before changing to next axis orientation. During the standard sinusoidal test (Fig. 6), the frequency of acceleration was increased from 10 Hz (at 0.511 g) to 2000 Hz at a rate of 1 octave/min. The final acceleration amplitude was 20 g. At 2000 Hz, the sweeping frequency was decreased at 1 octave/min until the vibration table acceleration frequency reached 10 Hz. Similarly, during the high-level short-duration sinusoidal test (Fig. 7), the acceleration frequency was increased from 10 to 250 Hz at a rate of 0.166 Hz/s. The sweep was also reversed after reaching 250 Hz. Two orthogonally mounted accelerometers were mounted on the table for reference measurements. During testing, a spectrum analyzer was used to verify radio frequency transmissions from the RDAU. During testing, the CCU was placed in the vibration table control room.

Before testing each axis, the RDAU was turned power-on to verify operation. Shortly after the sinusoidal sweep started, the RDAU was commanded to record 10 s of data. Audio and acceleration measurements acquired during the Z-axis vibration tests are shown in Fig. 8 for 0.05 s. The dc bias was 38 counts. Accelerometer gains

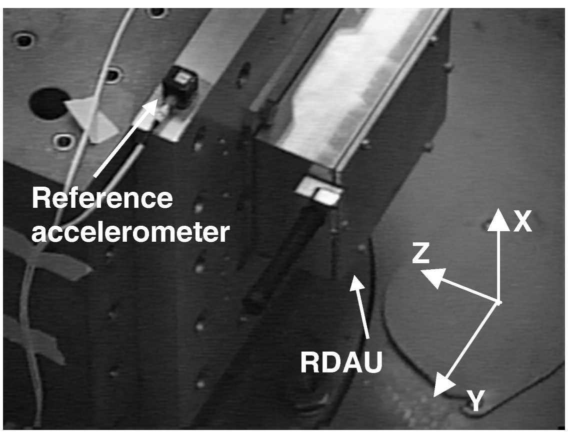


Fig. 5 Vibration table and RDAU during vibration testing; axis orientation of RDAU during vibration testing.

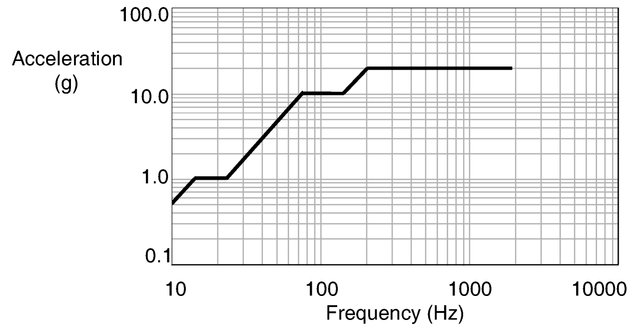


Fig. 6 Standard acceleration profile used during vibration testing for each axis.

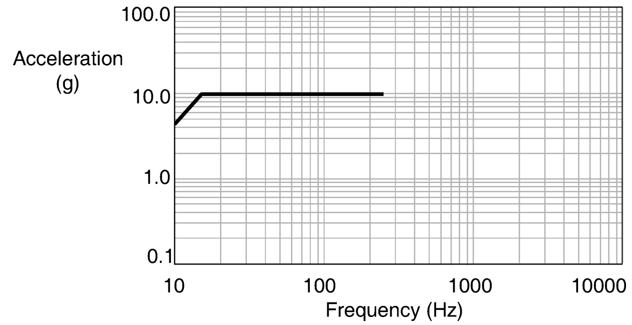


Fig. 7 Acceleration profile during vibration testing used for each axis.

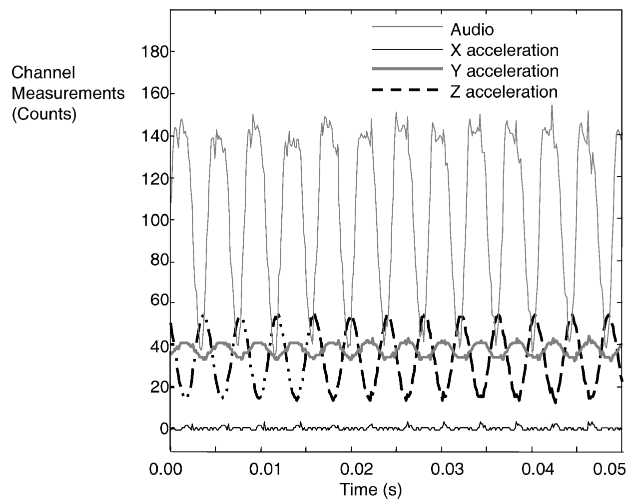


Fig. 8 Vibration response measured using RDAU during vibration test.

were set so that 125 $g =$ 128 counts. The measurements were taken when the table was in vibration at approximately 240 Hz. After each sinusoidal sweep has ended, the RDAU was commanded to download the data to the CCU. The CCU file directory was examined to verify the download. After the download was verified, the RDAU was commanded to the sleep mode. No malfunctions were observed for either the CCU or the RDAU during all vibration sweeps.

Electromagnetic Interference Testing

Research experiments that fly on the NASA LaRC Boeing 757-200 ARIES must be tested to determine if they cause electromagnetic interference to communication receivers and/or navigation receivers onboard the aircraft.[1,4] Aircraft-level testing was performed when there were major configuration changes on the 757 ARIES, for example, new experiments added. Experimental equipment is required to be cleared for all phases of flight, including takeoff and landing. Any interference to the communication and navigation equipment is a potential safety risk. Rollins[4] provides a very detailed description of the testing required for flight. Features of testing relevant to the health-monitoring system are summarized in this section.

The aircraft-level testing determined the interference from the research equipment to the communication and/or navigation receivers. Interference to other systems was determined during instrumentation check flights (ICFs). The aircraft-level testing provided the exact environment and radio frequency coupling paths thereby producing more accurate results than could be achieved if the individual instruments were examined in an electromagnetic interference laboratory. Because the radiated emissions profile for the research system was not known, the entire operational band was swept for each receiver.

Aircraft-level testing was performed after all research pallets passed flight quality assurance inspections. All research pallets were in flight configuration and were operating in a normal flight mode for this testing. The interference levels were measured at the antenna ports for each of the communication and navigation receivers and then the receivers were tuned to any suspect frequencies to determine if the level was sufficient to cause interference. The electromagnetic interference test measured the level of noise at the input to the receivers for example, very high-frequency omnidirectional range (VOR), instrument landing system (ILS) localizer, etc., listed in Table 2. Operational frequencies for the receivers are also listed in Table 2.

During measurements, the applicable aircraft receiver's antenna was used as the measurement antenna. The signal received from the antenna is used as the input to a spectrum analyzer. The measurement scan of the receiver band was first performed with all research equipment powered-off. The applicable receiver frequency band was scanned using the spectrum analyzer. A minimum of three sweeps was made at each frequency band to determine the baseline response and to ascertain any significant noise present. The purpose of the baseline scan was to identify any noise that was not due to the research system. Next, the measurement scan was performed with all of the research equipment powered-on. Any noise signals measured are compared to those recorded in the baseline scan. If the signal was not previously identified, the frequency and level are recorded and the signal plotted. Next, the research pallets were powered-down one at a time while displaying each identified signal. The source of the potential interference signal was identified when the signals were not present when the equipment was powered-off. Once the research pallet was identified, individual equipment on the pallet was powered-on and -off to determine the source of the interference within the research equipment. This procedure was repeated for each receiver listed in Table 2.

Table 2 Receiver antenna port measurements

Receiver measured	Frequency range, MHz
Marker beacon	74.8–75.2
Very high-frequency omnidirectional range (VOR)	108–118
Instrument landing system (ILS) localizer	108.1–112
ILS glideslope	328–335
Ultra high frequency (UHF)	225–400
Very high frequency (VHF)	118–138
Distance measuring equipment (DME)	960–1220

After the potential interference was identified, a receiver check was performed. The receiver check determined which potential interference signals were of sufficient strength to cause interference to the communication receivers. These frequencies of interference and the source of interference were reported to the pilots so that they were aware of any unusable communication frequencies. It is difficult to determine interference to the navigation receivers during the receiver checks. Therefore, all frequencies of potential interference to the navigation receivers were reported to the pilots, and the sources of the interference were noted so that the pilots were aware at what frequencies the receivers may experience interference.

By performing a functional check of critical and essential systems, the pilots determine any interference to other systems during the ICFs. The correct operation of the navigation receivers at the identified potential interference frequencies was also verified during the ICFs. A functional check of as many instrument operational modes as possible for the applicable phases of flight was performed.

The major source of electromagnetic emission from the health-monitoring system was from the use of the radio frequency transceivers. The transceivers operated at 433 MHz, which was above the UHF band (225–400 MHz) and significantly below the DME band (960–1220 MHz). The entire emission of the health monitoring system had no influence on the UHF antenna. No other communication or navigation systems had operational frequency bands for which the health-monitoring system could possibly interfere. The transmission frequency and harmonics did not fall within any of the communication and navigation radio frequency bands checked.

Hazard Analysis

Potential hazards were identified and analyzed to assure safety during the test flights. The initial flight tests were performed with the RDAU mounted on the tow fitting of the left main gear. Table 3 lists six potential hazards that were identified. The corrective and/or preventative actions are also included in Table 3.

ARIES

ARIES is a Boeing 757-200 that has had its cockpit and fuselage reconfigured to serve as a platform for experimental aerospace and atmospheric science systems. A detailed description of ARIES is given in Ref. 5. The aircraft characteristics are given in Table 4. The baseline research configuration of the ARIES includes 12 instrumented test pallets/research stations. Additional pallets and research equipment can also be installed. The pallets are primarily located in the passenger cabin. Each pallet has dual video monitors and an coordinated universal time (UTC) synchronized time display. Video cameras are located in the landing gear well pointing toward the gear, on the aircraft tail pointing forward, in the rear cockpit with view of cockpit, and forward cockpit providing a nose view.

Other equipment is located throughout the aircraft, such as research displays mounted in the forward flight deck and a telemetry pallet located in the aft life raft overhead storage compartment. There are external video cameras and various special-purpose antennas and sensors in other locations.

Flight Test Results

The RDAU and the CCU had 13 flight tests on the NASA LaRC ARIES. Four test flights were completed in August 2001. Nine additional tests were performed from March to May 2002. During all tests, a single RDAU was mounted on the left main landing gear, as shown in Fig. 9. The CCU was mounted in a research pallet (Fig. 3) of the NASA LaRC Boeing 757-200 ARIES. The flight-test objectives were to validate the wireless communication capabilities of the system, the hardware design, command and control, software operation, and data acquisition, storage, and retrieval. A very rigorous test of the mechanical design was achieved by mounting the device on the landing gear. The sensors listed in Table 1 were used

Table 3 Potential hazards associated with remote data acquisition unit being mounted on main landing gear

Potential hazard	Undesired event	Cause of potential hazard	Effect of undesired event	Corrective/preventative action
1) Controlled flight into terrain/loss of control/failure of landing gear to extend/retract due to electrical failure	Controlled flight into terrain/loss of control/failure of landing gear to extend/retract	Electrical shorting due to design error, installation error, or water intrusion	Loss of aircraft or serious injury or death	Hazards 1–4 Extensive airworthiness and safety reviews of the RDAU design and the preflight testing was used to alleviate the potential hazards identified Installment of all health-monitoring subsystems were given thorough flight quality assurance inspections.
2) Controlled flight into terrain/loss of control/failure of landing gear to extend/retract due to mechanical failure	Controlled flight into terrain/loss of control/failure of landing gear to extend/retract	Mechanical failure due to design error, fracture failure (affecting tires, brakes/antiskid, flaps, etc.), or mechanical interference with systems in wheel well (i.e., electrical, hydraulic. landing gear, brakes/antiskid, etc.)	Loss of aircraft or serious injury or death	
3) Damage or injury due to unintended release of stored energy in tires (pneumatic)	Damage or injury due to unintended release of stored energy in tires	Tires damaged due to mechanical failure of transmitter box or components	Tire damage, serious injury or death	
4) Foreign object hazard created on runway due to mechanical failure of transmitter unit	Foreign object damage on runway	Mechanical failure of transmitter unit	Aircraft damage, serious injury	
5) Controlled flight into terrain/loss of control due to electromagnetic interference (EMI)	Controlled flight into terrain/loss of control/failure of landing gear to extend/retract	EMI affects ship's avionics and/or nearby ground stations.	Loss of aircraft or serious injury or death	Hazard 5 1) EMI testing was performed to measure interference with RDAU operating at 433 MHz and 1 mW 2) Blackout zone was planned where transfer of data from RDAU(s) to CCU was not scheduled; zone was initially defined as lower than 1000 ft above ground level (AGL) 3) Tests and procedures were developed to ensure no impact on ILS when near ground or interference with B-757 avionics (e.g., no active or passive transmission during critical flight maneuvers) 4) No hardwired interface was allowed to B-757 aircraft systems
6. Damage or injury due to unintended release of stored electrical energy, radiation, or electrocution	Equipment damage or personnel injury	Batteries in transmitting unit explode due to high temperatures or charging failure	System damage, personnel injury, or death	Hazard 6 1) Batteries were not chargeable and were replaced on condition 2) Voltage outputs were monitored from experimental pallet and were used to predict replacement requirements 3) Batteries are sealed within a metal enclosure, which has been analyzed/reviewed for structural integrity 4) Five AA lithium batteries were mounted inside each RDAU 5) Transceiver power output remained at 1mW or below 6) Laptop batteries are considered to be in the normal flight use profile

a) Left main landing gear with RDAU **b) RDAU mounted on tow fitting of landing gear**

Fig. 9 RDAU mounted on NASA LaRC Boeing 757 main landing gear.

Table 4 NASA LaRC ARIES dimension and performance characteristics

Characteristic	Specification
Aircraft type	Boeing 757-200
Engines	Two Rolls-Royce RB211
Maximum thrust	43,100 lb
Wing span	124 ft 10 in.
Height	44 ft 6 in.
Length	155 ft 3 in.
Maximum take-off weight	230,000 lb
Maximum operating altitude	42,000 ft
Maximum speed	350 kn (Mach 0.86)
Acceleration force limits	2.5 to $-1.0\ g$

to measure and record acoustic and dynamic response in proximity to main landing gear. During the initial flight tests, none of the autonomous features had been installed. The system was functioning as a remotely controlled data acquisition device.

The four flight tests of 2001 validated the mechanical design and software design. Examination of data files verified that all commands transmitted from the CCU were received by the RDAU. However, when the RDAU was commanded to return a status code or data, the communication was not consistent. Signals from the CCU to the RDAU were sent by an encoder connected to the parallel port. This encoder takes 4 bits from the parallel port and encodes them into a special signal that can be transmitted by the transceiver. This encoded signal was repeated several times during the transmission to ensure it gets through. The RDAU has a decoder that is matched to the CCU transceiver encoder. However, data and status signals from the RDAU were sent back as a standard RS-232 signal from the RDAU computer. This signal was in the form of a packet that was recognized by the software in the CCU. A status reply was sent as one packet. The low-power transceiver required extremely good ambient radio frequency conditions for the RDAU signals to be received by the CCU. Incomplete packets were not recognized by the computer. The best conditions for reliable RDAU transmission and CCU reception occurred when the gear was down and the runway (or taxiway) area beneath the wheels was not covered with rubber tire marks. Conditions such as when the gear was retracted in the wheel well resulted in numerous loss receptions.

The encoder/decoder pairs were designed to be used in remote control applications. To improve reception of signals coming from the RDAU, an encoder was added to the RDAU computer parallel port, and a decoder was added to the CCU transceiver interface box. This encoded signal contained information on file storage and measurement acquisition mode. The redesigned health-monitoring architecture now has two methods to query the RDAU: the original RS-232 signal and the additional encoder/decoder pair. The modified architecture now has one encoder/decoder pair for sending CCU commands and another encoder/decoder pair for sending RDAU status and data.

The nine flights in 2002 were performed to evaluate the modifications made after the first series of flights. All modifications greatly enhanced the performance of the system. The 4-bit encoder resulted in better communication connectivity between the RDAU and CCU. Flight-test engineers were able to determine the recording status of the RDAU more reliably. For example, the flight-test engineers could easily determine whether the RDAU was armed, was triggered, or whether data had been collected. Other modifications between flight series were to mount sensors on RDAU casing and to have multiple files for storing measurements. The dc bias was changed to 138 counts. Accelerometer gains were changed from 2.47 to 1.66 resulting in 1 count = $1.45\ g$.

Measurements acquired during flights included takeoffs, landings, vibration while gear was fully retracted, taxiing, and, touch-and-go landings. A measurement of a touch-and-go landing is shown in Fig. 10. The measurement is taken from the accelerometer along the aircraft roll axis. The landing event was approximately 15 s in duration. The objective of the measurements was not to analyze the measured data but to validate the means to acquire the measurement. Figure 10 shows that the remotely controlled data acquisition capability works. A similar profile was obtained from the audio measurements of channel. The measurements shown in Fig. 10 showed similar characteristics to other acceleration measurements taken duirng the flight tests in 2002.

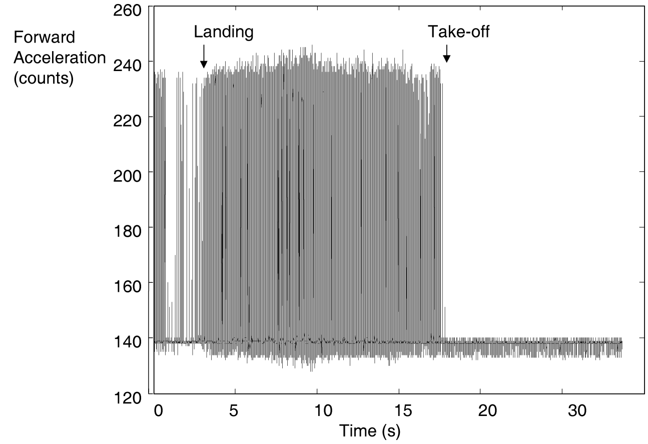


Fig. 10 Acceleration along roll axis measured by RDAU during touch-and-go landing at Langley Air Force Base, 24 April 2002: DC bias = 138 counts, 1 count = 1.45 *g*.

Future Work

Key attributes of the system have been demonstrated during flight tests on the NASA ARIES. The next phase of development is to apply expert systems that have been also developed at NASA LaRC. The expert systems use parameterized fuzzy logic algorithms that allow the input-output mapping to be tuned. The expert systems will be installed to provide a means for performing autonomous analysis.

Other future work is to use Linux operating systems at all operational levels of the architecture. The final goal is to install RDAUs throughout the aircraft and perform flight tests to demonstrate all operational levels including the TCU currently under development. All amplitude shift keying modulation transceivers will be replaced with frequency-modulated transceiver with variable power control (1–10 mW). A frequency-modulation transceiver is less susceptible to noise. Secured wireless cell phone chips are another possible communication option.

Future development goals of the RDAU include lowering power consumption. The hardware casing is to have a smaller volume and area footprint. Sensors will be external to the housing and placed on flex circuits. The unit will have a wireless laptop/desktop personal computer control, communication, and collection interface. The unit will have the ability to use vehicle power. New versions of the digital interface will have the processing capability of the onboard computer currently being used. The dual functionality of the digital interface will make it possible to eliminate the onboard computer. The digital interface requires less power consumption, thereby requiring fewer batteries. The volume and area footprint of the RDAU will greatly be reduced because the RDAU computer is removed (less area) from the circuit board and fewer batteries are required (less volume). Many of the operational features of the RDAU will be transitioned into a system-on-chip-based design. System on-chip (SoC) incorporates the processor and most of the peripherals and interfaces onto one chip. Benefits of SoC include reduced physical properties (mass, dimensions, power), reduced printed circuit board layout, flexible external interface capability, and ease of software/hardware integration, as well as reduced development through software/hardware codesign methods allowed by such a design. This type of design can be implemented using available FPGA, CPLD, and highly integrated microcontroller offerings from various companies.

The future design changes to the CCU are to make the unit portable and self-contained. The unit is to be placed within a small volume ruggedized chassis that should make the unit easy to carry.

The transceiver circuitry shall be placed within the chassis. The CCU will also have a keypad interface and liquid crystal display. The CCU will use external power source but have lithium batteries as a power backup. SoC design will also be incorporated into future CCU designs to make the architecture attractive to small privately owned aircraft and other smaller vehicles.

Conclusions

On-going development and testing of an adaptable vehicle health-monitoring architecture has been presented. The objective of the health-monitoring architecture is to reduce vehicle operating costs, improve safety, and increase reliability. The architecture is being developed such that it can be retrofitted into a fleet of vehicles. There are three operational levels to the architecture: one or more RDAUs located throughout the vehicle, a CCU located within the vehicle, and a TCU to collect analysis results from all vehicles.

Fuzzy expert systems will be implemented in all operational levels. The expert systems are developed such that they can be trained for any vehicle or structure to perform autonomous analysis. The expert systems are parameterized to allow them to be adapted to a given suite of sensors. Expert systems provide a means to include a user's subjective reasoning and quantitative methods into autonomous analyses. Once a suite of sensors are chosen for each RDAU and located on the vehicle, a baseline of acceptable vehicle performance is established from measurements acquired when the vehicle is performing within design specifications. The RDAU embedded expert system can then be trained to its respective baseline.

The architecture provides an infrastructure for performing tributary analyses. The measurements collected at the lowest level are analyzed at that level. Analysis results are forwarded to next operational level, and then all results are analyzed to ascertain global trends or anomalies for the prior level. This is repeated until all analyses are combined at the highest level. The advantage of the having expert systems at each analysis level is that it can eliminate the need for transmitting and storing large volumes of collected measurements. Forwarding only analysis results to the next operational level reduces telemetry congestion.

The RDAU has an eight-channel programmable digital interface that allows the user discretion for choosing type of sensors, number of sensors, sensor sampling rate, and sampling duration for each sensor. The parameterized trainable fuzzy expert system and the programmable digital interface make health-monitoring hardware and software infrastructure adaptable to many vehicles and structures.

All communication within the architecture is done with wireless transceivers operated at 433 MHz and 1 mW. EMI tests have demonstrated that the radio frequency emissions from the transceivers have no influence on any of the civilian aircraft communication and navigation antennnae. The RDAU has been thermally tested for temperatures ranging from -50 to 55°C. Pressure testing verified that the RDAU could be used in nonenvironmentally controlled spaces on an aircraft at 50,000-ft altitude. Vibration tests verified that the RDAU could operate during vibration representative of that which commercial aircraft experience. During vibration testing, the final acceleration amplitude was 20 g at 2000 Hz.

Potential hazards were identified and analyzed to assure safety during the test flights. Extensive airworthiness and safety reviews of the RDAU design and the preflight testing was used to alleviate the potential hazards identified. Installment of all health-monitoring subsystems was given thorough flight quality assurance inspections.

There were 13 flight tests of the remote data acquisition unit and the command control unit on the NASA LaRC Boeing 757. The flight tests were performed to validate the following: the wireless radio frequency communication capabilities of the system; the hardware design, command, and control; software operation; and data acquisition, storage, and retrieval. A very rigorous test of the mechanical design was achieved by mounting the device on the left main landing gear. During the initial flight tests, none of the autonomous features had been installed. The system functioned as a remotely controlled data acquisition device.

Four test flights were completed in August 2001. The four flight tests of 2001 validated the mechanical design and software design. The tests indicated that radio frequency communications needed to be modified to be more reliable. Another 4-bit encoder/decoder pair was added to the system. Multiple data storage files were added. The nine flights in March–May 2002 were used to evaluate the modifications that were made after the first series of flights. All modifications greatly enhanced the performance of the system. The final series of flight tests demonstrated that the remotely controlled data acquisition capability worked correctly.

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