DEVELOPMENT AND FLIGHT TESTING OF AN AUTONOMOUS LANDING GEAR HEALTH-MONITORING SYSTEM

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Abstract. 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 the vehicle; a command and control unit located within the 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. 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 non-analysis software have been flight tested on the NASA Langley B757's main landing gear. 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.

1 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 existing aircraft and thus provide them with state-of-the-art health monitoring capabilities. The objective of the health monitoring system is to reduce vehicle operating costs, improve safety and increase reliability. Frequent vehicle monitoring allows identification of the embryonic stages of damage or degradation. The architecture provides a means to identify vehicle subsystem degradation or damage before they become costly and/or disastrous. 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.

The architecture is a hardware and software infrastructure for health monitoring that can be easily developed to a health monitoring system. Ref. 1 provides detailed descriptions of the architecture, airworthiness pre-flight qualification testing, expert system development and flight test results. The architecture presented herein is being developed for a fleet of vehicles. It has three operational and analysis levels: one or more remote data acquisition units (RDAU), a command and control unit (CCU), and a terminal collection unit (TCU). 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[1, 2]. The programmable data acquisition circuitry allows type of sensor and number sensors used to be at the discretion of the user. The circuitry allows the sampling rate for each sensor to be programmed. Wireless radio frequency transceivers are used to communicate with all of the architecture components.

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.

The system’s remote data acquisition hardware and non-analysis software has been flight tested on the NASA Langley B757’s most severe location to mount a health monitoring device: the landing gear. NASA Langley’s Airborne Research Integrated Experiments System (ARIES) is a Boeing 757-200 which is described in detail in Refs. 1 and 3. Following the introduction will be an overview of the architecture hardware and software. Results from the airworthiness pre-flight tests (pressure, vibration, thermal and electromagnetic interference testing) will be presented next. Hazard analysis will follow. Flight tests results are presented next.

2 ARCHITECTURE OVERVIEW

The architecture is developed as a framework for tributary analysis for a fleet of vehicles. The three sub-systems of the health monitoring architecture are the remote data acquisition unit, the command and control unit and the terminal collection unit[1]. The details of each sub-system will be presented in this section.

The architecture is capable of performing tributary analyses. The measurements collected at the lowest level are analyzed at that level. Analysis results are forwarded to a higher 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.

Each analysis level can incorporate a trained expert system. Having expert systems at each analysis level can eliminate 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 systems are developed such that they can be adapted to any system. The lowest level consists of one or more remote data acquisition units (RDAU) capable of collecting and analyzing data. Each RDAU has 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 command and control unit (CCU). The CCU is capable of performing vehicle level analysis. Each RDAU analysis results are forwarded to the CCU that can perform similar analysis but for all RADUs (i.e., the vehicle big picture). Global anomalies to the vehicle can be detected. The fused analysis can also be used to locate anomalies by triangulation. Spatial trends can also be identified using the fused analysis results. After the end-of-flight, a vehicle's CCU analysis is then forwarded to a terminal collection unit at the airfield. The terminal collection unit functions as a repository of all vehicle analyses and performs analyses using results forwarded from all vehicles. Here all vehicles can be compared to ascertain if there are common anomalies (e.g., vendor supplied bad brake pads, improperly manufactured linkage, etc).

2.1 Remote Data Acquisition Unit (RDAU)

Remote data acquisition units (RDAU) are multi-sensor interfaces with an on-board miniature computer, programmable digital interface, nonvolatile solid-state memory and a wireless transceiver for communication with the command and control unit. The RDAU electronics and housing are shown in Fig. 1a. The unit is shown in Fig 1b mounted on the main landing gear. The software embedded in the RDAU computer provides transceiver control, encoder/decoder control, data file management. The autonomous analysis capability is currently being added to the architecture. The computer controls all functions for communication, data acquisition and storage. Sensor data is acquired via a flexible sampling scheme through a programmable digital interface. Currently a disk operating system (DOS) is being used which is to be replaced with a Linux operating system. A remote data acquisition unit can accommodate eight sensor measurements. Five AA Lithium batteries are used to supply power to each RDAU. External power sources can also 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 non-environmentally controlled locations of the plane. The device can operate at -50°C to 55°C and pressure equivalent to 50,000 ft altitude.

Any combination or type of sensors can easily be installed into the RDAUs. These sensors can be within the RDAU housing or external to the RDAU (e.g., connected with wires or flex circuits). Data acquisition circuitry is implemented in a single complex programmable logic device (CPLD). A complex programmable logic device can be reconfigured in-circuit. A device performing a similar function is a field programmable gate array. The circuitry controls all analog-to-digital conversion. A first in/first out sample buffer and the buffer status is regulated by the circuitry. Time division multiplexed (TDM) 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.

A transceiver operating at 433MHz was used for communication with the command and control unit. The transceiver used 1mW of power. The transceiver used amplitude shift keying modulation (somewhat similar to amplitude modulation). The frequency does not electro-magnetically interfere with aircraft communication and navigation systems. A micro-controller regulates the transceiver power management logic. The transceiver power management algorithm regulates the RDAU transceiver to power-off for 2 s, then power-on for 2 ms to acquire any commands broadcast from the command and control unit. It then returns to power-off for 2 s if no commands are broadcast. The algorithm continuously cycles the transceiver power in the aforementioned fashion. If there are broadcast commands, the transceiver remains on until the commands are completed. Each RDAU has an addressable encoder/decoder. Commands can be received directly through the encoder/decoder. RDAU status and data are received through serialized packet format.

Each RDAU can sense numerous physical attributes (e.g., sound, heat, or mechanical disturbance) within vicinity of a RDAU. Measurements during the flight tests were acceleration in velocity direction; acceleration along pitch axes; acceleration in vertical direction; sound; RDAU temperature; and battery voltage. In nominal operation, each physical attribute sensed by a sensor interfaced to a RDAU has a performance envelope or established pattern that are 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. Basically, each RDAU has a collection of measurement signatures (i.e., profiles) established from measurement during correct and non-damaged operations of the system. Measured profiles that show alterations to the signatures infer the system has changed.

2.2 Command and Control Unit (CCU)

The command and control unit is a computer-based subsystem that provides the communications, analysis repository, and user interface functions for RDAU control, data archiving, and analysis. The command and control unit is shown in Fig 2a. Fig 2b shows the transceiver for the CCU. The CCU can also serve as a power management tool by regulating when individual or combinations of RDAUs are powered on. A simple radio frequency (RF) wireless network of RDAUs can be controlled from a single CCU. Communication, for RDAU control, is provided via a custom wireless RF transceiver interface. The CCU can be manually controlled and reconfigured via standard computer interfaces (e.g., standard serial cable to a portable PC such as a laptop, personal digital assistance; or, keypad). If the CCU must be embedded further into the vehicle/plant, control and configuration could be carried out remotely via a RF communication. A user interface is provided to allow the user to control functions for a selected RDAU. Data and/or analyses, downloaded from the associated acquisition units, are archived for the next level of analysis.

The CCU regulates the health monitoring architecture. It has a wireless transceiver to communicate with all RDAUs via two-way RF. The CCU controls all RDAUs with the following commands: power on-off, acquire, trigger, stop, reset, status and download. It has the ability, using expert systems, to reduce and analyze all data collected. The CCU can be controlled and reconfigured manually by use of any portable PC such as a laptop, personal digital assistant via a standard serial port. A keypad with LCD display is also part of the CCU. Currently a disk operating system (DOS) is being used which is to be replaced with a Linux operating system.

2.3 Terminal Collection Unit (TCU)

The terminal collection unit (TCU) provides the means to autonomously retrieve vehicle analysis results from all vehicle CCUs. The TCU performs analysis on all results collected from all vehicles to identify any fleet-wide anomalies (e.g., all aircraft have the same faulty bearing at a similar location). The TCU will be used to develop the final summary of the vehicle health monitoring results that gets routed to the appropriate users (e.g., maintenance workers, airlines operations, etc.). The TCU is currently under development. A portable system that contains the non-analysis capabilities of the TCU has been successfully demonstrated to download data after flights. The TCU is embodied as a Linux-based processor with RF communication, internet connectivity, expert systems and installed software similar to that to be 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 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 shell commands which query the appropriate directories for new analysis reports and then to forward reports via emails or file transfer protocols.

3 AIRWORTHINESS PRE-FLIGHT TESTING

Pre-flight tests were performed to validate the airworthiness of the remote data acquisition unit. The tests were to verify the operation of all electrical components, software and radio frequency communication. The tests performed were thermal cycling, pressure, vibration and electromagnetic interference. The integrity of the mechanical design which included housing and mounting of electrical components was partially verified during vibration testing. The pre-flight airworthiness tests were performed in accordance to Ref 4. The complete validation of the design was the objective of the flight tests. Detailed results of testing are provided in Ref. 1.

3.1 Thermal Testing

The remote data acquisition unit 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 eight continuous hours. The temperature rate of change between the holding periods was approximately 2.5°C per minute. Temperature variation for flight qualification was from 20°C to -40°C to 55°C to 20°C. The temperature was held constant for at least one hour at each of the aforementioned temperatures. During preliminary testing, the temperature varied from 20°C to -50°C to 20°C. The temperature was maintained at -50°C for 5 ½ hours during preliminary testing.

Operation of the unit was verified throughout the testing. At each measurement time, the RDAU was commanded by the CCU to power on, acquire data, transmit data to CCU and then power off. The RDAU functioned correctly at all measurement points for all tests.

3.2 Altitude Testing

To emulate pressure conditions at 50, 000 ft, the RDAU was placed in a Process Equipment Co. 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 initiated with the chamber temperature at ambient temperature. The RDAU was positioned in the chamber so that it could be viewed through the front window of the chamber. Since 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 command and control unit or by the RDAU. During testing, the CCU was external to the vacuum chamber. The RDAU was tested prior to 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 two hours. The RDAU performance was monitored during the two hours by acquiring measurements from all channels every 30 minutes. 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.

3.3 Vibration Testing

To verify that the remote data acquisition unit could operate during vibration that was representative of what commercial transports could experience, the RDAU was subjected to a vibration test. A T1000 Unholtz-Dickie vibration table was used to provide the desired acceleration. The RDAU was subjected to the two sinusoidal vibration spectrums. Both sine-sweep tests were conducted in each axis before changing to next axis orientation. During the first sinusoidal test, the frequency of acceleration was increased from 10 Hz (at 0.511g) to 2000 Hz at a rate of 1 octave/min. The final acceleration amplitude was 20g. At 2000 Hz, the sweeping frequency was decreased at 1 octave/min until the vibration table acceleration frequency reached 10 Hz. Similarly, during a second high-level short duration sinusoidal test, the acceleration frequency was increased from 10 Hz to 250 Hz at a rate of 0.166 Hz/s. The sweep was also reverse after reaching 250 Hz. Two diagonally 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. The command and control unit was placed in the vibration table control room.

Before testing each axis, the RDAU was turned POWERED ON to verify operation. Shortly after the sinusoidal sweep started, the RDAU was commanded to record 10 seconds of data. The measurements were taken when the table was 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.

3.4 Electromagnetic Interference Testing

Research experiments that fly on the NASA Langley Research Center (LaRC) Boeing 757-200 Airborne Research Integrated Experiments System (ARIES) must be tested to determine if they cause electromagnetic interference to communication receivers and/or navigation receivers on-board the aircraft.[4, 5] Any interference to the communication and navigation equipment is a potential safety risk. C. H. Rollins provides (Ref. 4) 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 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 airborne radio frequency receivers. The respective operational frequencies for the receivers are marker beacon (74.8 – 75.2 MHz); VOR (108 –118 MHz); ILS localizer (108.1 – 112 MHz); ILS glideslope (328 – 335); UHF (225 – 400 MHz); VHF (118 – 138 MHz); and DME (960 – 1220 MHz).

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 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 radio frequencies communication and navigation bands checked.

3.5 Hazard Analysis

Potential hazards were identified and analyzed to assure safety during the test flights. The initial flight tests were performed with the remote data acquisition unit mounted on the tow fitting of the left main gear. The potential hazards were controlled flight into terrain/loss of control/failure of landing gear to extend/retract due to mechanical failure, electrical failure or electromagnetic interference (EMI); damage or injury due to unintended release of stored energy in tires (pneumatic); and damage or injury due to unintended release of stored electrical energy, radiation or electrocution; and foreign object hazard created on runway due to mechanical failure of transmitter unit. Extensive airworthiness and safety reviews of the remote data acquisition unit design and the preflight testing were used to alleviate the potential hazards identified. Installment of all health monitoring subsystems were given thorough flight quality assurance inspections. EMI testing was performed to measure interference with RDAU operating at 433 MHz and 1 mW.

FLIGHT TEST RESULTS

There were 13 flight tests of the remote data acquisition unit and the command and control unit on the NASA Langley ARIES. Four test flights were completed in August 2001. Nine additional tests were performed from March –May 2002. During all tests, a single RDAU was mounted on the left main landing gear as shown in Fig 1b. The command and control unit was mounted in a research pallet of the NASA Langley Research Center (LaRC) Boeing 757-200 Airborne Research Integrated Experiments System (ARIES). Fig. 2 shows the CCU and its radio frequency antenna. The flight test objectives were to validate the following: 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 placed in the RDAU were used 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 four 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 main 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 were not covered with rubber tire marks. Condition 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 used to evaluate the modifications that were 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, 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.

Measurements acquired during flights included take-offs; 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 3. The measurement is taken from the accelerometer parallel to the velocity of the aircraft. 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. Fig 3 demonstrates that the remotely controlled data acquisition capability works.

CONCLUDING REMARKS

On-going development and testing of an adaptable vehicle health-monitoring architecture has been presented. 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 remote data acquisition units located throughout the vehicle; a command and control unit located within the vehicle; and, a terminal collection unit to collect analysis results from all vehicles. The next phase of the architecture development has already commenced. It includes installing autonomous capability for data reduction and analysis using the expert systems. Finally, in this next phase, the RDUA units will also be placed throughout the aircraft.

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

Potential hazards were identified and analyzed to assure safety during the test flights. Extensive airworthiness and safety reviews of the remote data acquisition unit 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 and control unit on the NASA Langley Airborne Research Integrated Experiments System (ARIES). 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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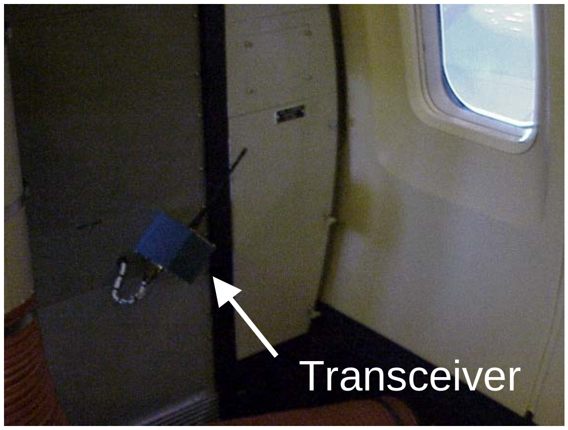
a. Remote data acquisition unit electronics

b. RDAU mounted on tow fitting of landing gear

Fig 1. Remote data acquistion unit (RDUA) electronics and mounted on NASA Langley Boeing 757 main landing gear.



a. Command and control unit mounted on NASA Langley Boeing 757 experiment pallet

b. Command and control unit transceiver mounted at rear of experiment pallet

Fig. 2 Command and control unit

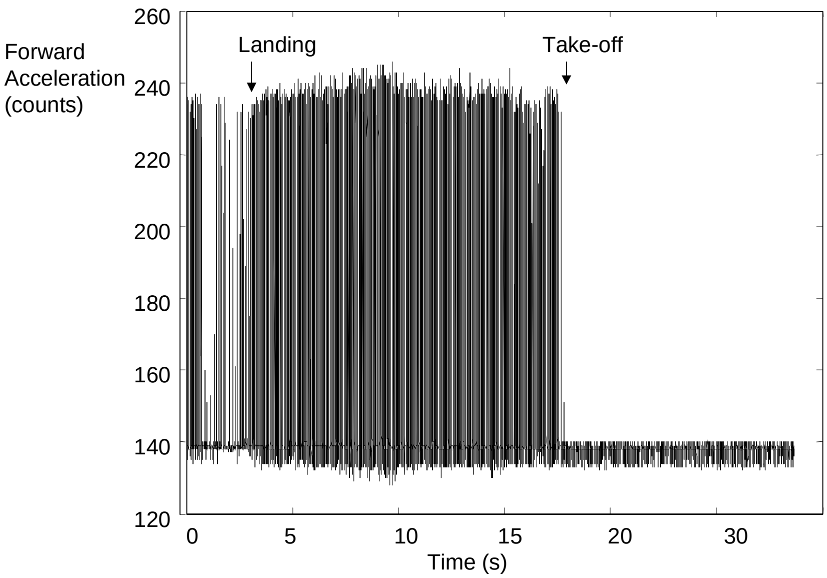


Fig. 3 Forward acceleration measured by RDAU during touch and go landing at Langley Air Force Base (April 24, 2002)