The 5th International Conference on Emerging Ubiquitous Systems and Pervasive Networks
(EUSPN-2014)

Emerging Needs for Pervasive Passive Wireless Sensor Networks on Aerospace Vehicles

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Abstract

NASA is investigating passive wireless sensor technology to reduce instrumentation mass and volume in ground testing, air flight, and space exploration applications. Vehicle health monitoring systems (VHMS) are desired on all aerospace programs to ensure the safety of the crew and the vehicles. Pervasive passive wireless sensor networks facilitate VHMS on aerospace vehicles. Future wireless sensor networks on board aerospace vehicles will be heterogeneous and will require active and passive network systems. Since much has been published on active wireless sensor networks, this work will focus on the need for passive wireless sensor networks on aerospace vehicles. Several passive wireless technologies such as microelectromechanical systems MEMS, SAW, backscatter, and chipless RFID techniques, have all shown potential to meet the pervasive sensing needs for aerospace VHMS applications. A SAW VHMS application will be presented. In addition, application areas including ground testing, hypersonic aircraft and spacecraft will be explored along with some of the harsh environments found in aerospace applications.

Keywords: Passive; Wireless; Sensor Network; Aerospace

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1. Introduction

Wireless ubiquitous devices have been proposed to aid in many aircraft maintenance tasks such as reporting, documentation, asset tracking, and inspections [1-3]. However, NASA researchers desire pervasive vehicle health monitoring systems (VHMS) sensor networks on board aerospace vehicles.

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Selection and peer-review under responsibility of Elhadi M. Shakshuki.

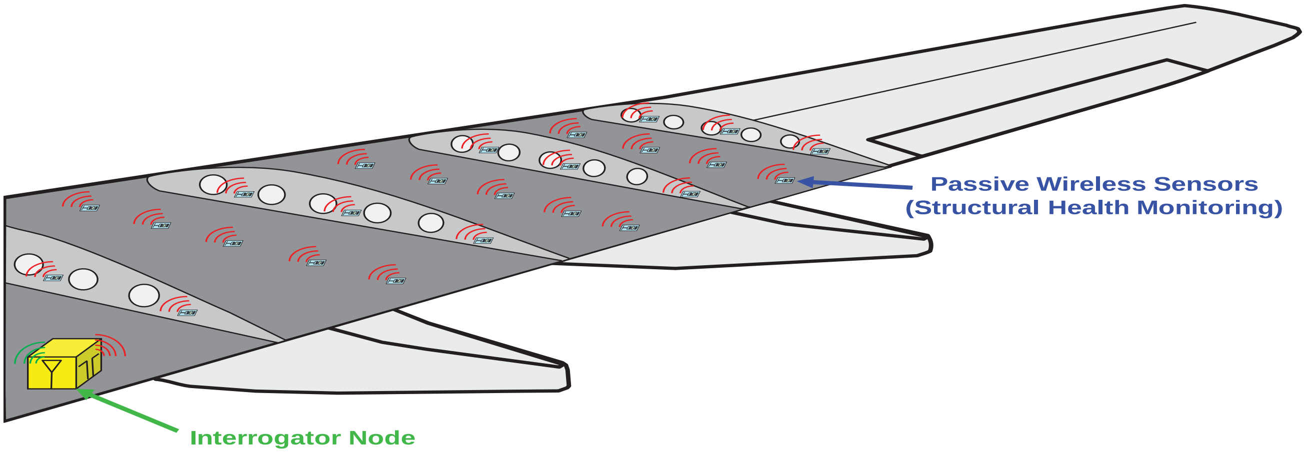

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Fig. 1. Concept for pervasive passive wireless sensors for structural health monitoring for aerospace vehicles.

The proposed VHMS system would introduce passive wireless sensors attached to the structure for health monitoring. The interrogator node would interrogate the passive wireless sensors and would communicate wirelessly to conventional wireless sensor networks in a heterogeneous manner (Fig. 1). For complete VHMS coverage, many sensors would have to be attached to the vehicle's structure. However, constraints such as cost, mass, volume, and power often prevent the inclusion of wired VHMS instrumentation into aerospace systems. The elimination of wiring and wiring harnesses could reduce the total mass of the vehicle by 6~10% [4], and will reduce the impact of mass constraints from a VHMS system [5]. For example, the Space Shuttle had 300 miles of wiring which weighed over 17,000 pounds [6]. Much of this weight could be reduced by using passive wireless sensors. In addition to reducing weight, eliminating wiring and the supporting infrastructure will reduce fabrication costs [7]. Wires are prone to damage, such as nicks and breaks, and degradation due to wear, excessive heating, and arcing. Wiring problems can also stem from poor workmanship, such as improper crimps during initial fabrication or re-work. Wiring problems have led to major aircraft accidents and space vehicle launch delays [8]. When retrofitting a structure with VHMS sensors, using wireless instead of wired devices will avoid the need for expensive cable routing redesigns and the costs associated with performing safety re-certifications [9]. For these reasons, wireless microelectromechanical systems (MEMS) sensors are a priority technology that warrant NASA's attention during the next decade [10]. Unfortunately, existing wireless sensor systems have low data rates and require batteries; these two conditions make such systems undesirable. However, high data rate systems that do not require batteries, such as passive radio-frequency identification (RFID) sensors, are being developed.

The environments surrounding aerospace vehicles are typically harsh, with temperature extremes ranging from cryogenic to very high (>1000°C) for hypersonic (greater than Mach 5) vehicles experiencing aerodynamic heating due to skin friction. Hypersonic aircraft based on NASA's HyperX X-43 design will fly at Mach 10 and therefore require sensors that can withstand temperatures up to 1,282°C [11]. Many of these hypersonic vehicles contain cryogenic tanks requiring sensors that operate in very low temperatures >-150°C. Thus, hypersonic vehicles will need passive wireless sensors that can operate in harsh environments, such as those needed for other aeronautical applications.

Sensors are typically located in internal spaces allowing limited access, making the necessary periodic changing of batteries costly and time consuming. Furthermore, batteries perform poorly in extreme temperatures. In contrast to current wireless systems, passive wireless surface acoustic wave (SAW) sensors operate without batteries across a large temperature range. Passive wireless sensor networks are an emerging technology due to the numerous applications with limited use for battery-based systems. As a result, NASA is investigating the use of passive wireless sensors for aerospace applications because this technology could benefit many NASA missions. Small, passive, pervasive, wireless sensors that can operate in harsh environments will have applications in ground testing, conventional aircraft, hypersonic aerospace vehicles, rockets, and spacecraft.

The main challenge for wireless sensors is power [12]. As previously mentioned, batteries often cannot be used due to inaccessible locations or exposure to large temperature extremes. Only energy harvesting systems that do not need batteries for energy storage can be used. Therefore, many researchers are investigating passive wireless sensing systems. Several passive technologies may be adapted to meet the needs of pervasive sensing for aircraft VHMS applications. MEMS, SAW, microwave backscatter, and passive or chipless RFID techniques have all shown potential for passive operation [13]. Passive wireless RFID chips have been developed that use RF energy to power the circuitry comprising the wireless sensor node [14]. RFID devices have also been proposed for use in smart skins for aircraft, among other applications [15]. A backscatter device that used reflected microwaves for measuring strain has been developed for structural health monitoring applications, including aircraft [16]. Another backscatter device has been developed for temperature sensing [17]. The device uses resonators to modulate the frequency of the backscattered radar cross section to make measurements. SAW devices have been proposed as passive wireless devices that can operate in harsh environments such as aircraft engines [18]. One passive wireless SAW sensor has demonstrated the ability to measure temperatures up to 910°C [19]. Any of these technologies may hold the answer to pervasive wireless sensors for aerospace applications.

2. SAW VHMS Device

Since SAW devices are small, low power, tolerant to radiation, and work in harsh environments at temperatures between -200°C and 910°C, the authors at NASA are investigating them for aerospace applications. For VHMS applications, a SAW device was fabricated on Langasite ($La_3Ga_5SiO_{14}$) substrate. The sensor has four Orthogonal Frequency Coded (OFC) reflector gratings that spread the device's response across multiple frequencies using OFC reflectors [20]. The gratings are grouped into two reflector banks. To avoid interference, the reflector banks are positioned on either side of an interdigitated transducer (IDT) and are spaced so the reflections do not overlap in time (Fig. 2).

The reflector banks are spaced 1.722 mm (left) and 3.710 mm (right) from the IDT. The number of fingers in each grating is 98, 99, 100, and 101. The four gratings have frequencies of 300.05, 303.04, 306.10, and 309.28 MHz arranged in order from f1, f2, f3, to f4, with f1 closest to the IDT. More diverse frequency arrangements comprising a reflector bank would allow more code diversity when uniquely identifying the sensor in a multisensory environment [21].

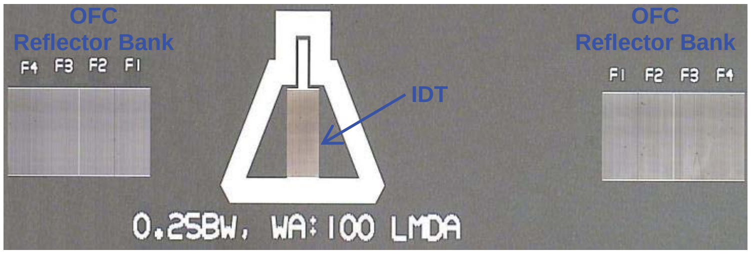


Fig. 2. SAW strain sensor comprised of an interdigitated transducer (IDT), and two banks of four OFC reflectors on a Langasite substrate.

The IDT must be broadband and encompass the frequency content of all four reflectors so it effectively has 23 finger pairs, a center frequency of 304.61 MHz, and a null bandwidth of 13.25 MHz for the main lobe. The reflectors have a null bandwidth of ~3.061 MHz each. The IDT fingers are 1.5 μm wide by 899.83 μm in length.

The SAW device can be used to take measurements because physical changes in the device will result in a change in operating frequency. Expansion of the SAW device results in a decreased operating frequency due to tensile strain or a temperature increase, while contraction due to compressive strain or reduced temperature results in an increase in the operating frequency. These changes are due in part to a change in the wavelength and a change in the average propagation velocity of the surface acoustic wave. The velocity changes are due to changes in the stiffness parameters and the density of the material [22].

To demonstrate its capabilities, the SAW device is measuring strain on a panel with bolted side stiffeners to simulate repeatable fastener failure. This panel is similar to panels suggested by Worden for structural health monitoring [23]. The aluminum panel is 635 mm wide and 939 mm long. The panel is 2.29 mm thick, aluminum (6051 alloy). The side stiffeners are made of 254 mm "L" shaped aluminum (6051 alloy) extrusions that are 1.587 mm thick. The bolts are spaced 50.8 mm apart. The root of the panel mounts to a steel plate using 26 bolts and a 629 mm x 50.8 mm x 76.2 mm base plate of aluminum on top of both the panel and side stiffeners. To distribute the force from hanging weights, a 629 mm x 25.4 mm x 12.7 mm steel plate attaches to the end of the panel.

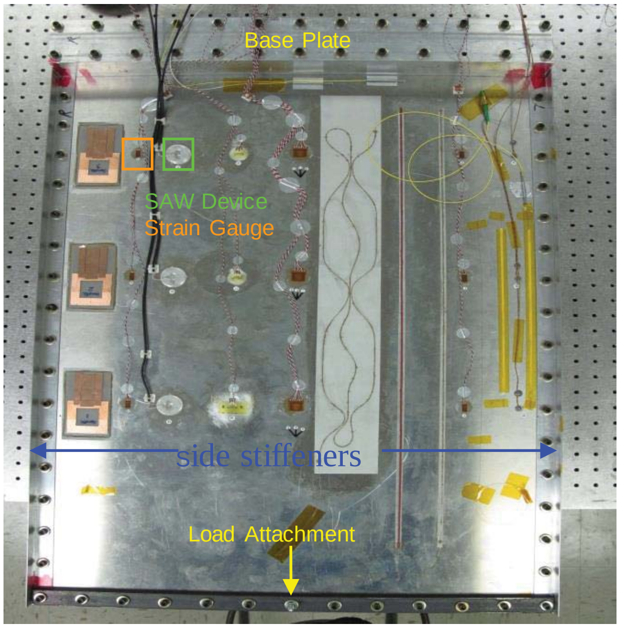


Fig. 3. Aluminum panel with side stiffeners used to demonstrate SAW fastener failure detection and strain measurement capabilities.

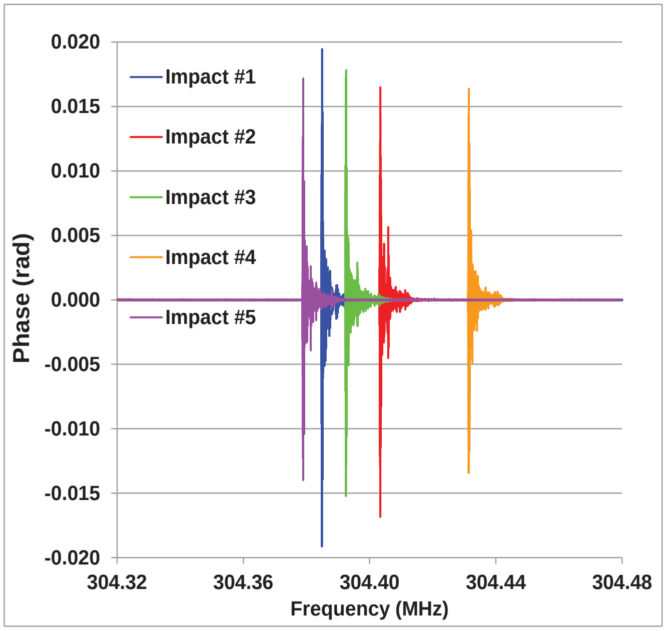


Fig. 4. SAW response to impacts without noise (Impacts #1 and #2) and with noise (Impacts #3, #4, and #5).

The panel was used as a test bed to investigate the feasibility of *wired* SAW sensors in a variety of structural health applications, such as strain and temperature [24]. An OFC SAW strain sensor, a type-K thermocouple, and a 350 Ω foil strain gauge were bonded onto the panel (Fig. 3). The SAW device can act as a fastener failure sensor by monitoring the strain on a vibrating panel with multiple loading conditions [25]. To demonstrate the SAW sensor's ability to detect impacts, a 46 g mass was dropped from a height of 46 cm onto the panel 51 cm away from the SAW sensor, which results in an impact energy of 0.208 J (Fig. 4). This experimental setup is commonly used in impact detection studies [26]. A shaker was used to simulate structural vibrational noise on the panel during some of the impacts. Although there was some variation in the amplitudes of the impacts, the results are generally consistent for both cases without noise (Impacts #1 and #2) and with noise (Impacts #3, #4, and #5). The average signal to noise (SNR) ratio for all five impacts is 51.03 dB. These results were very encouraging in relation to the use of the SAW sensor as an impact detector in the presence of noise.

To demonstrate its ability to measure strain *wirelessly*, the SAW device on the panel was connected to a helically wound, 315 MHz, quarter-wave antenna. A matching antenna was connected to the network analyzer. Measurements were taken as the load was increased from 0 kg to 4.0 kg in 1 kg steps at room temperature. The results are given in Fig. 5. The SAW strain measurements agree with the strain gauge. This initial testing demonstrates the SAW sensor's ability to become a passive wireless sensor with the addition of only an antenna. The plan is to continue characterizing the SAW device as a passive wireless sensor for use in VHMS applications. Work will also continue on optimizing the SAW devices to increase the transmission distance. Potential flight-testing opportunities and relevant ground tests is also being investigated.

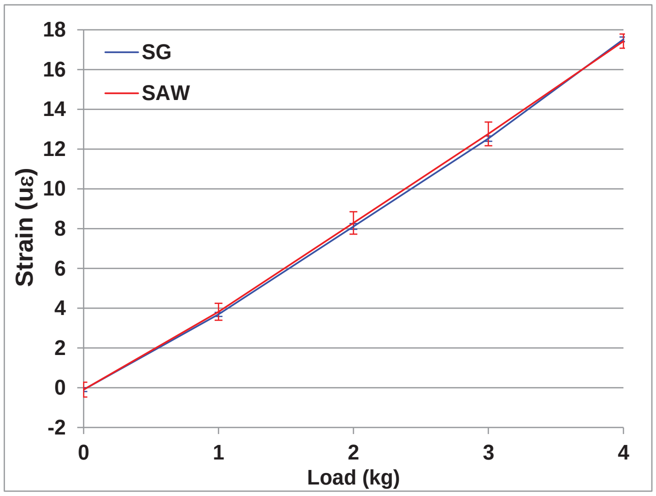


Fig. 5. Wireless SAW strain sensor versus strain gauge. Error bars indicate one standard deviation.

(a) (b)

Fig. 6. (a) Accelerometer wiring hanging down from an F/A-18 test aircraft at NASA Armstrong Research Center.
(b) Strain gauge wiring (orange wires) installed on the interior of the AFTI/F-16 wing.

3. Wireless Sensor Networks for Aeronautical Test Applications

In addition to the SAW research, NASA is also looking to industry and universities to develop other wireless sensors. Wireless sensors could be used during all phases of aeronautical research. NASA performs many tests on components and systems on the ground before any flight testing occurs. These tests require placing a large number of sensors on the test article. Currently, very few sensors have been connected wirelessly. These tests are initially performed on models and test articles in NASA's wind tunnels. The sensor suite inside wind tunnel models includes a variety of sensors, such as pressure, temperature, strain, shear stress, and accelerometers. The sensors and their associated wiring generally take up most of the available space within the model. After the model is instrumented, it is mounted to the sting inside the wind tunnel using a balance block. Wind tunnel test data would be improved if all the wiring crossing the balance block were removed. The environment for wind tunnel models at NASA is quite harsh. Temperatures can range from -157°C inside the National Transonic Facility to 2,616°C inside the Arc Heated Scramjet Facility; the pressure can be as high as 27.6 MPa [27]. Very small, passive wireless sensors that can operate in extreme environments would be extremely useful for this application.

In addition to wind tunnel tests, NASA also performs many ground tests involving aircraft and aircraft components. For example, Fig. 6(a) shows numerous accelerometer wires installed during vibration testing of the Active Aeroelastic Wing F/A-18 test aircraft at the NASA Armstrong Research Center. The blue actuator cylinder (on the lower right) generates vibrations into the airframe during the tests; which are used to determine if aerodynamically induced vibrations are controlled or suppressed during flight. For loads testing on the same wing, 200 strain gauges, 54 string potentiometers, and 32 load cells were used [28]. To prepare for another load test, the skin from an AFTI/F-16 aircraft wing was removed to install strain gauges. Fig. 6(b) shows the strain gauge wiring installed on the interior of the wing. For applications such as these, passive wireless sensors could be permanently installed internally. The sensor locations are inaccessible; therefore, they obviously prohibit the use of batteries that would need periodic changing.

4. Wireless Sensors for Space Test Vehicles

NASA also has a need for passive wireless sensing on spacecraft during flight and while being tested on the ground. To support a fueling test for monitoring cracks on the space shuttle Discovery's external tank, 60 thermocouples and 39 strain gauges were installed [29]. Numerous sensor cables were attached to the gantry structure and routed to instrumentation (Fig. 7). This wiring could be eliminated with wireless sensors. Of course, the sensors would need to operate near cryogenic temperatures for this application.

Fig. 7. Instrumentation wiring for testing the structural integrity of the space shuttle Discovery's external tank.

NASA's Space Launch System program is developing a new series of rockets known as Ares and a new crew exploration vehicle known as Orion [30]. NASA has identified that the Orion capsule would benefit greatly from wireless sensors [31]. The wireless system needs to be low mass and flexible for both new needs and rapid implementation. The system requires high channel counts with distributed storage. Each channel requires a large dynamic range with high sample rates and needs to operate in harsh environments. The Orion capsule design mainly uses aluminum, a well-established and proven aerospace material. However, the NASA Engineering and Safety Center (NESC) formed a multi-center team in 2006 to investigate the design of an all-composite crew module (CCM) (Fig. 8). This module was developed in parallel to its aluminum counterpart to determine the feasibility of flying an all-composite spacecraft. The team was "to perform a preliminary design and characterize additional design drivers as they apply to composites, such as manufacturability, crashworthiness, damage tolerance, inspectability, repairability, and the effects of micro-meteoroid orbital debris (MMOD) impacts."[32] This design effort led to the fabrication of a full-scale composite capsule; this capsule was delivered to NASA for testing in the Combined Loads Test System (COLTS) facility. Parts were tested for loads and impacts, and the entire structure was subjected to static testing at 31 psi (two atmospheres) internal pressure. For testing at the COLTS facility, the CCM was instrumented with 280 strain gauges, 3000 FO strain gauges, and 80 acoustic emission sensors. Many of the measurements were designed to give data that would be instrumental in developing a VHMS system for the operational capsule. The external sensor cabling is clearly visible in Fig. 8. Tests such as these could benefit from wireless sensors to reduce the amount of cabling, debugging, and setup time for ground testing applications.

NASA has also developed the Max Launch Abort System (MLAS), which is an alternative launch escape system to the rocket tower placed on top of manned rocket systems. Fig. 9 (a) shows the MLAS, which is comprised of four solid rocket motors attached under the manned capsule and inside a protective composite fairing. The MLAS was launched on July 8, 2009 from Wallops Island in Virginia; Fig. 9 (b) shows the MLAS during launch. The main objective of the launch was to test for a stable trajectory during an unpowered portion of the flight. To monitor the capsule during flight, ~176 sensors were flown. These sensors included 87 pressure sensors, 52 strain gauges, 23 accelerometers, and 13 thermistors. A passive wireless implementation could have reduced the wiring weight of this suite of sensors.

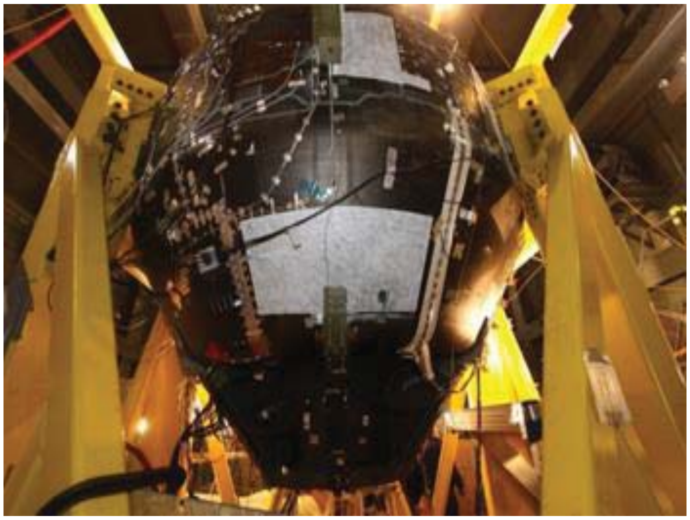
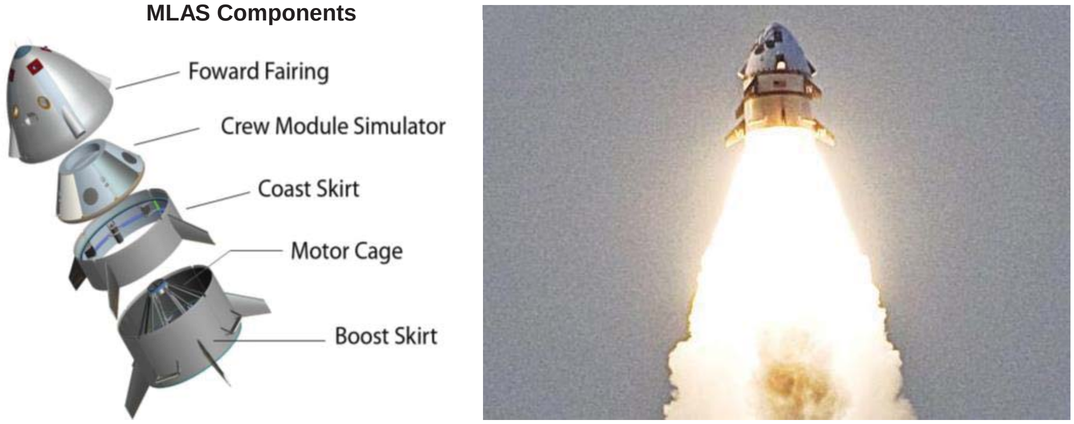


Fig. 8. NASA's composite crew module



(a) (b)

Fig. 9. (a) NASA's Max Launch Abort System (MLAS); (b) MLAS during launch from NASA's Wallops Island Facility

RFID sensor tags were used as part of the Smart and Intelligent Sensor Project (SiSP) for the MLAS [33]. The RFID tags were used to identify transducer electronic data sheets (TEDS) for legacy non-smart sensors. Although the tags were not flown, they were part of a payload demonstration project that included a suite of new smart sensor and wireless technologies that were evaluated for flight readiness. The use of the tags in ground support equipment and comparisons with the flight payload measurements will aid in increasing the technology readiness level and the likelihood of future flight opportunities for RFID sensors. While this example used ground-based testing, the Orion crew module could benefit from a subset of these sensors if they were flight qualified.

The Ares series of rockets was developed to launch the Orion crew capsule into space. The Ares 1-X rocket launched on Oct. 28, 2009 (Fig. 10) with more than 906 sensors on board as part of the Development Flight Instrumentation (DFI) system [34]. The sensors measured aerodynamic pressure and temperatures at the nose of the rocket and contributed to measuring vehicle acceleration and angle of attack. Of the 906 sensors listed as components of the DFI, 689 were low-data-rate sensors: 112 temperature sensors, 98 strain gauges, 108 accelerometers, and 371 pressure sensors. Passive wireless sensors could eliminate all the cabling weight for these measurements. SpaceX and Orbital Sciences Corporation have won NASA contracts to develop new commercial rockets that can carry supplies to the International Space Station (ISS). These new rockets will have the same requirements for low mass, low power, and passive wireless sensors.

5. Conclusions

Aerospace vehicles have many applications that could benefit from pervasive passive wireless sensor networks. Eliminating wiring from ground tests, wind tunnel tests, research aircraft, and spacecraft will reduce mass and implementation times. Wireless sensor networks have the potential to increase the quality of data from wind tunnel tests. Passive wireless sensor technology will enable VHMS to incorporate numerous sensors in inaccessible locations on aircraft, thereby increasing aviation safety. In addition, NASA is investigating the use of wireless technology for a variety of spacecraft applications. SAW passive wireless strain sensor device for VHMS applications have been demonstrated. SAW technology is one possible solution for aerospace applications; other technologies may also be part of the solution, such as MEMS, passive RFID, and backscatter. NASA is looking to industry and universities to develop some of the new wireless sensor technologies.

Fig. 10. Ares I-X rocket launching from Pad 39B at NASA's Kennedy Space Center

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