FLY BY WIRELESS

Introduction:

The increasing adoption of composite materials in aircraft manufacturing offers the benefits of reduced weight, improved structural strength, as well as high corrosion resistance. However, composite structures are vulnerable to low to medium velocity impact events causing barely visible damage, such as debris, hail or, tool drop during maintenance.

In aerospace engineering, reducing the system weight while maintaining the operation safety is one of the challenges in aircraft or space vehicle design. Composite materials, due to the improved mechanical properties, high corrosion resistance and reduced weight, become an ideal option for designers. These materials, consequently, are increasingly being used in aircraft primary structures including B787, Airbus A380, F35, and Typhoon. However, composites are vulnerable to impacts, even those at low velocities

WIRELESS SENSING SYSTEM DESIGN :

System Configuration and Operation Principle

The wireless passive module developed in this work belongs to a wireless sensor network covering the whole aircraft, to continuously monitor the structural integrity and potential impact events, as shown in Fig. 1. In such a network, there is one network coordinator that receives data from distributed end devices. Each of them oversees several sensors within a certain area. If an impact event occurs, the sensor node in the local region will record all the outputs from the sensors within the local area, and wirelessly transmit the data to the coordinator, and the coordinator will conduct the signal-processing algorithm and evaluate the impact event. For the hardware design, the system is required to be able to record any concerning impact events over a large sensing area. In addition, other considerations, including system added weight, device dimension, power consumption, costs and system robustness are essential and inevitable. A system design considering all the factors in a holistic manner is required for practical applications. For signal post-processing, the system will, in the first place, determine the location where an impact has occurred using the time of arrival information. Then, the impact intensity and materials can be estimated using the time and frequency domain characteristics. The detailed methodology will be discussed in the following sections. Three levels of impact severity, including ’safe’, ’alert’, and ’damaged’, are designed, and the impact events can be classified into different levels according to pre-defined thresholds.

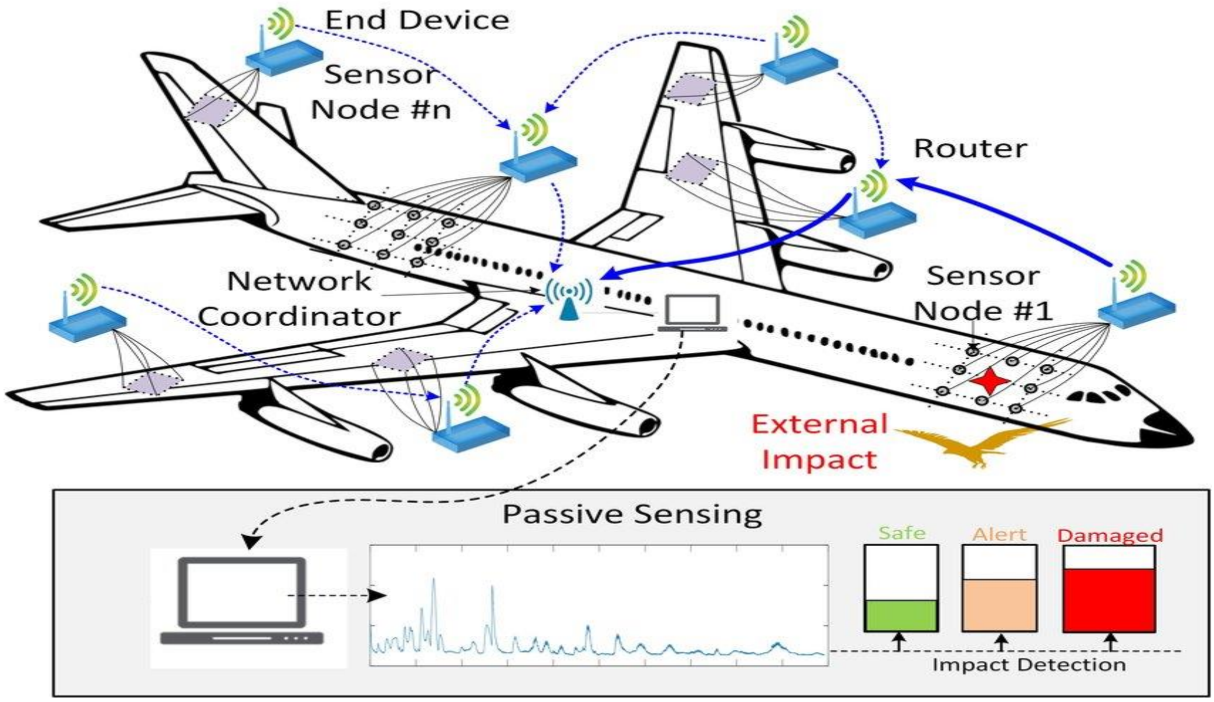

Figure 1. System configuration and operation principle. Wireless passive sensing devices are mounted on an aircraft. A wireless sensor network is established to fulfil the impact detection, data communication and signal processing functions.

Passive Sensing Hardware Design

The design of the passive sensing module is illustrated in. The main functions and operation principle are depicted in **Fig. 2(a)**. Piezoelectric transducers (PZTs) are mounted or embedded on composite structures. A sensor node is designed to manage a group of PZTs mounted the local area. The PZTs' outputs are connected to the ADC channels on the sensor node. In order to avoid environmental noises (operation vibration), a filtering module is adopted to eliminate the operational disruption. Bridge rectifiers are used by converting the alternative outputs from PZTs to DC values suitable for the sensor node. As impact events are typically rare, transitory and random, different operation modes are ideal for the sensor node to both monitor alarming events and to save energy when no events occur. A comparator module is designed to fulfil this function. A threshold Vd is pre-set. This value is used in the comparator module to determine if any PZT outputs are higher than the threshold. A trigger will be generated if one channel is higher than Vd. This trigger is used to transfer the sensor node from a low power sleeping mode to a high-performance processing mode. Waking-up delay should be properly designed to ensure the impact events can be recorded with enough details. All the outputs from all PZTs in the local region are recorded and processed in the local sensor node. Then, the processed data are transmitted to the central station (in Fig. 1) wirelessly using a wireless transmission module. Then, the whole system turns into the low-power mode to save energy. The central station will evaluate the influence of the event on the structural integritybased on the received data.

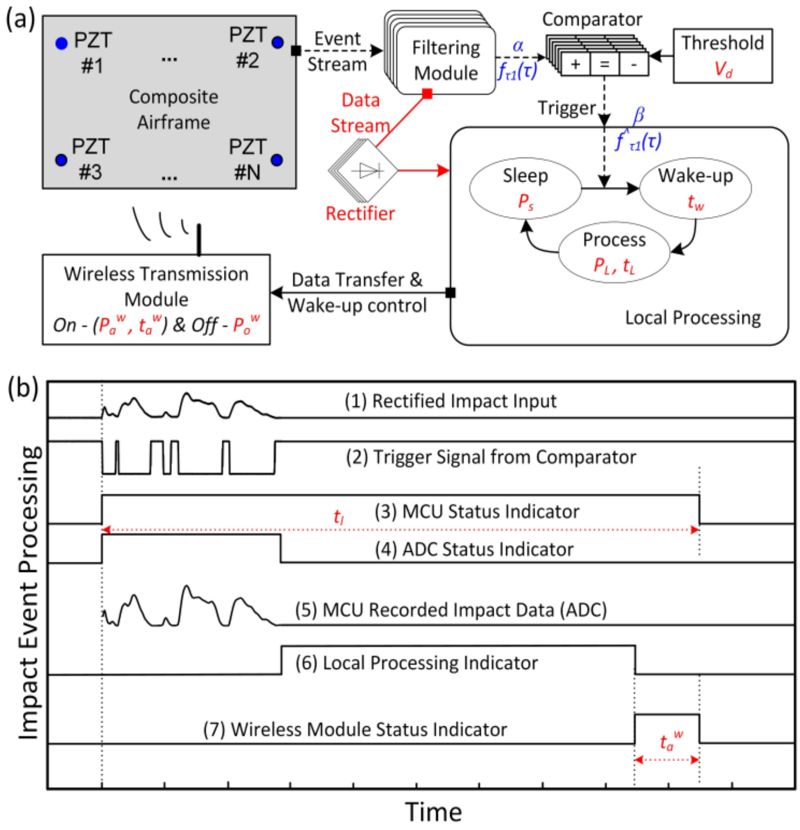

Figure 2. Design and operation illustration a passive sensing node in a wireless sensor network. **(a)** System design and function diagram and **(b)** impact event processing procedure, showing the operation principle.

Fig 2(b) explains the impact event processing steps of the sensor nodes. When an impact event occurs, the PZTs record the structural dynamics in a form of voltage **(1)**. If the output voltage is larger than the preset value, a trigger **(2)** is generated by the comparator module to wake up the sensor node from the sleeping mode. The sensor node, then, starts recording all the output signals from PZTs in the local region **(3)-(5)**. The recorded signals are processed (6), before they are wirelessly transmitted to the central station **(7)**. Several design considerations should be satisfied to ensure the system performance.

• System wake-up delay. As indicated in **Fig 2(b)(5),** the beginning part of the impact signals can be lost due to the system wake-up delay. This delay is mainly caused by the response time of the comparator module, the amplitude of the threshold value, and also the response time of the local processing module in the sensor node after being triggered. Appropriate electronics should be selected to reduce this system delay, while maintaining low system power consumption.

• Sampling rate. A sufficient sampling rate should be adopted to ensure the signal authenticity.

• ADC input channels. As a wireless sensor node is in charge of multiple PZTs in a local region. A larger monitoring region can be covered by one sensor node if the node possesses a larger number of ADC channels.

SYSTEM IMPLEMENTATION

Hardware Implementation

Fig. 3 illustrates the implementation of the hardware design on a printed circuit board (PCB) and an illustration of the appearance of such a device in practice. The hardware is implemented on a 2-layer PCB with the dimensions of **100 mm × 65 mm**. 12 input channels were implemented for sensing. High pass-filters, bridge rectifiers and comparator modules were designed individually for each input channel for recording and pre-processing input signals from the PZT sensors on composite structures. A micro-controller from the STM32L4 family was adopted for the local processing module. It provides a clock frequency up to **80 MHz** and multiple operational modes suitable for low-power operation. An XBEE ZigBee module was used in this device for wireless communication. The communication range can be up to 60 m(indoor)/1200 m(outdoor). provides an illustration of a conceptual design of such a device with a casing. This device can be amounted inside the fuselage to monitor external events. **Fig. 4(a)** shows a fuselage design and sensor placement for testing. 12 PZT sensors were mounted on the inner surface of the fuselage. In order to mimic impact events in a controllable manner, an impactor was mounted on an adjustable impact stand, as shown in **Fig. 4(b).** Different impact energy levels and locations can be obtained by adjusting the height and position of the stand. The developed hardware in **Fig.3(a)** is connected to the 12 PZT sensors on the fuselage, and the system performance was tested under different conditions.

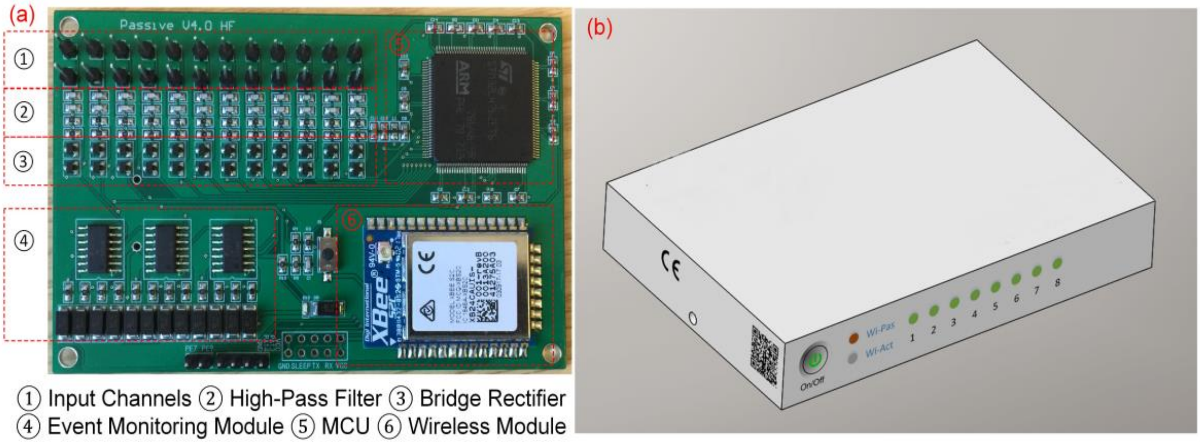

Figure 3. Hardware implementation of the wireless sensing system on a printed circuit board **(a)** and an illustration of the device for practical installation **(b).**

Energy-Based Impact Evaluation

As piezoelectric sensors can be modelled as capacitors in parallel to a current source, the instantaneous energy generated on the piezoelectric sensors can be expressed as

$$E_{in} = \frac{1}{2} C_{pzt} V^2,$$

where Cpzt is the capacitance of PZT sensors and V is the output voltage. According to Eq. 1, the instantaneous energy is proportional to V 2 . Therefore, an Energy-Based parameter is better than the Voltage-Based method in terms of de-noising and enhancing the significance of the signals from the direct-path (initial signal packages). Here, we also define another performance measure that will be used in the following analysis, Average Stored Energy, which can be expressed as

$$E^j_{avg} = \sum_{i=1}^{N} E^{ij}_{in} / N,$$

where j = 1, 2, ..., 12 is the channel sequence, N is the total number of data recorded from 1 sensor and i = 1, 2, ..., N. This performance measure illustrates the average energy generated on 1 PZT sensor for a specific recording duration. Fig. 6 illustrates the results from impacts applied on the same location but with different input energy levels. Instantaneous generated energy is indicated in the colour bar in Fig. 6(a)-(c), and average stored energy is used in Fig. 6(d)-(f). According to the variation of the colour distribution in Fig. 6(a)-(c) and the height of the bars in Fig. 6(d)-(f). The input energy level can be easily identified and classified.

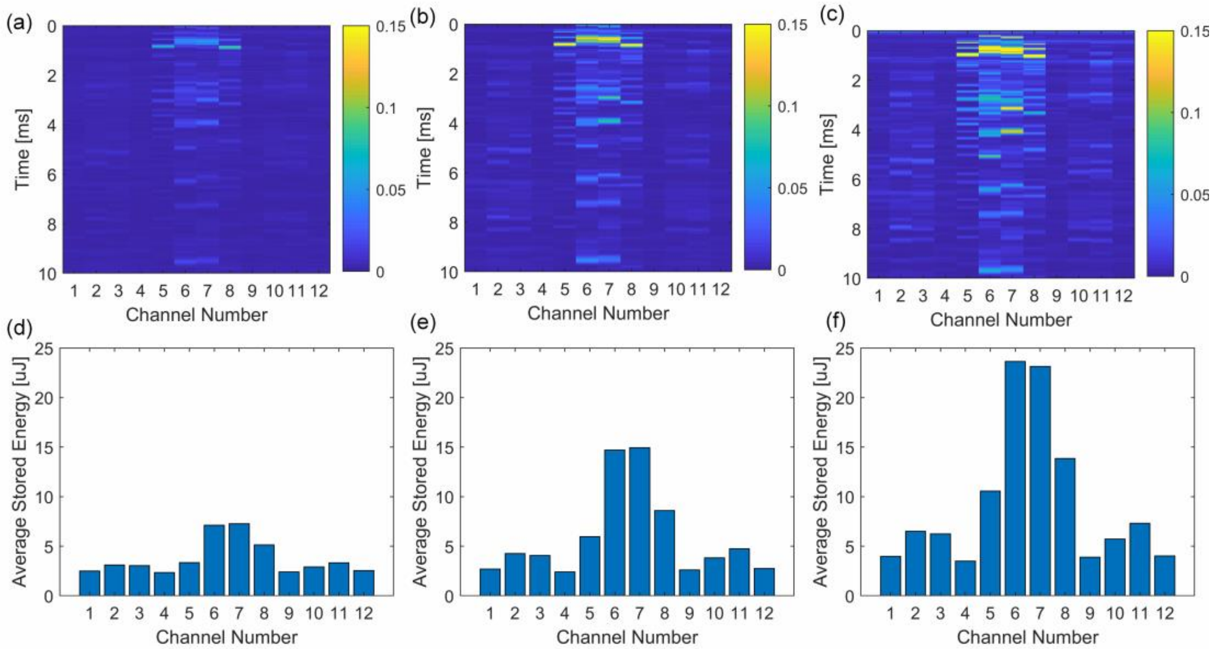

Figure 6. Instantaneous generated energy [(a), (b) and (c)] and average energy [(d), (e) and (f)] for different channels in time for different impact energy levels applied on the same location between PZT 6 and 7. Impact input energy level: (a) and (d) low; (b) and (e) medium; (c) and (f) high.

Then, these measures are used to evaluate impact events applied on different locations with the same input energy. The results are shown in Fig. 7. These impacts were applied right in the middle between two sensors, e.g. PZT 1-2, PZT 6-7, or PZT 11-12 in sequence. According to the distribution of the color or the time of arrival variation, the impact location can be easily identified. If a higher localization accuracy is required, deep learning algorithms can be solutions to provide a more reliable and accurate evaluation using the generated figures in Fig. 7. A large set of 115 random impacts with different energy levels was conducted in the region confined by PZT 6 and 7. The average stored energy was calculated and plotted in Fig. 8. Three different zones are introduced using pre-defined thresholds. This figure illustrates how impact events are finally classified into different levels. The thresholds for different zones can be obtained from practical operation testing and statistical data. Based on the impact event evaluation, certain reports and required inspection or maintenance actions are generated and delivered to aircraft operators.

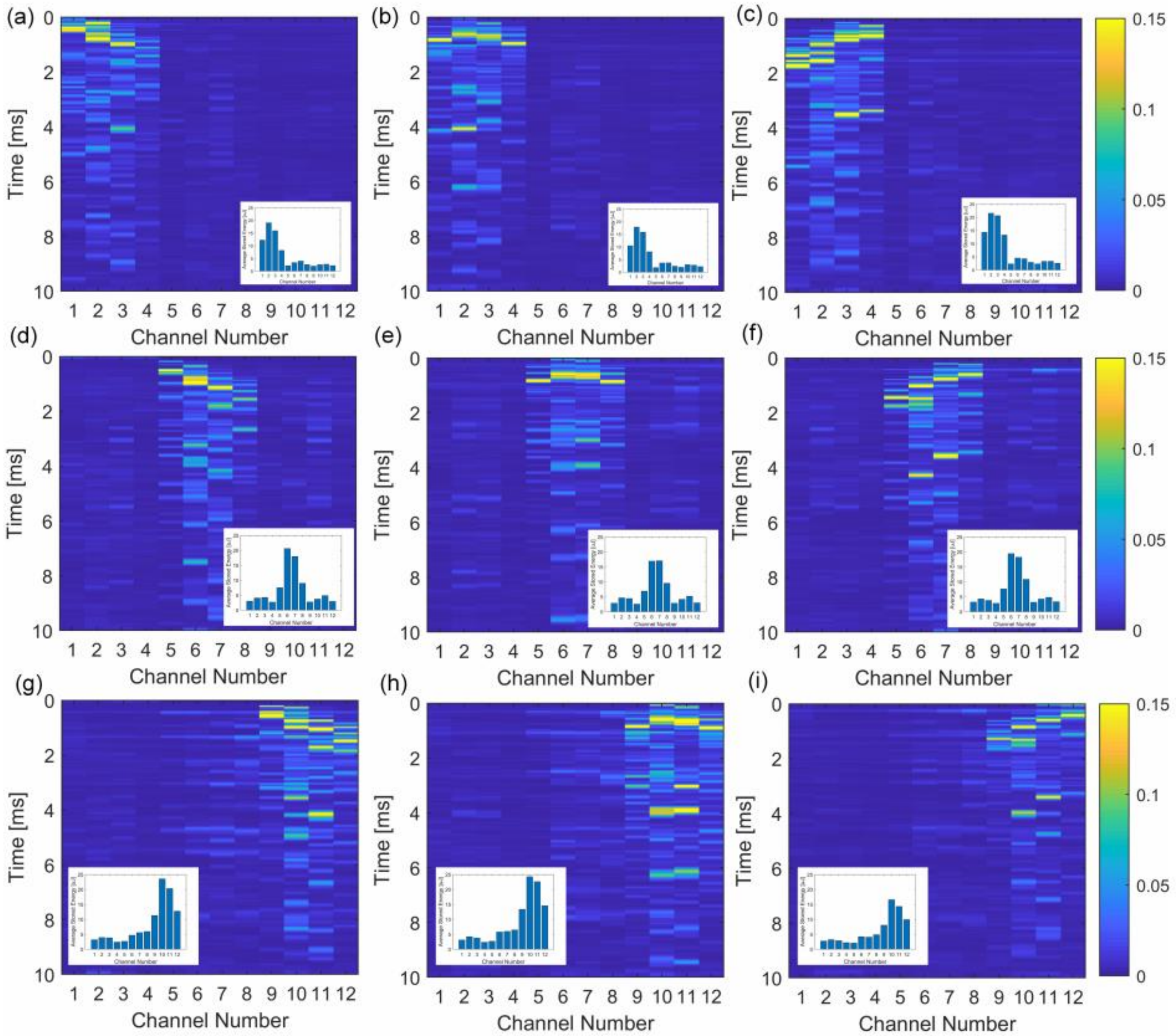

Figure 7. Instantaneous and average stored energy for different sensors under impacts applied on different locations with the same input energy. The impact location can be identified by the variation of the colour distribution.

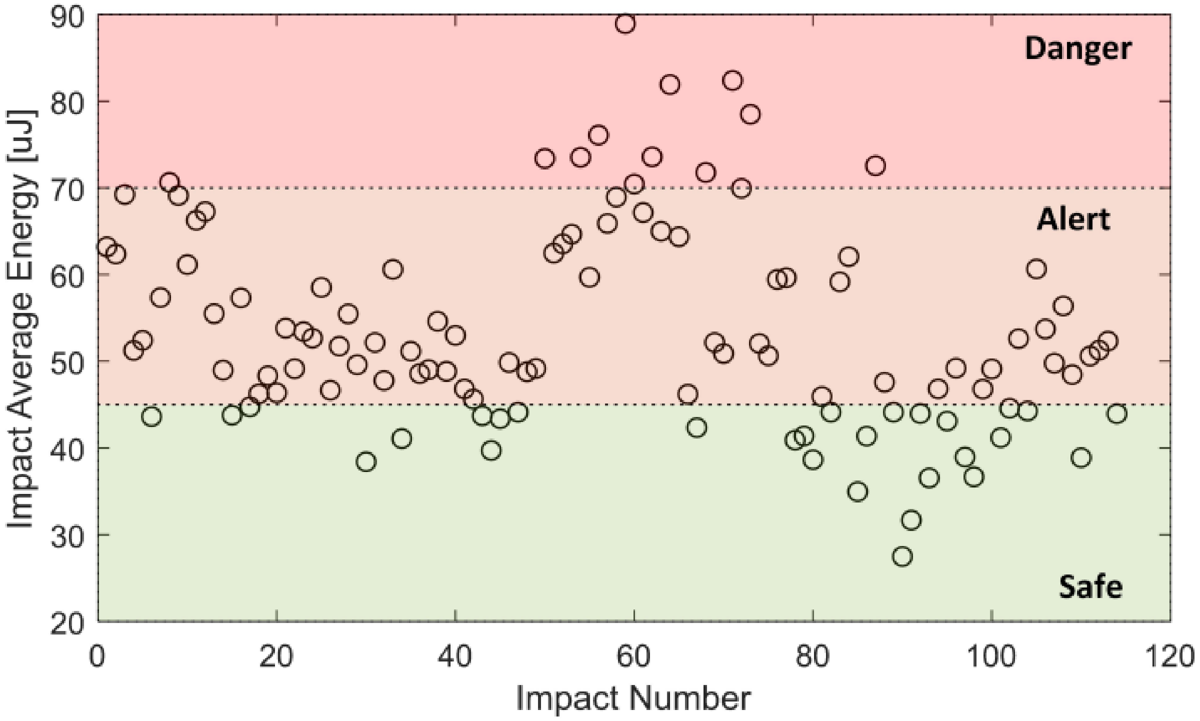

Figure 8. Random impacts applied in the zone between PZT 6 and 7 in the middle of the bay in Fig. 4(a), showing the results of the classification of impact events based on the recorded impact response.

CONCLUSION AND FUTURE WORK

In this paper, a wireless sensing module for impact detection on aerospace composite structures was presented and assessed. The system's operational principle and hardware design are discussed, showing the capability of the system in detecting impact events while maintaining a low-power consumption, high compactness and wireless communication capability. The hardware design was implemented on a printed circuit board with the dimensions of 100 mm× 65 mm. The system performance was evaluated on a large-scale composite fuselage, showing the multiple channel performance in impact detection. An Energy-Based method is proposed in this paper for localizing, evaluating and classifying impact events with different input energy levels on different locations. Future work will be on testing the system in operational conditions with the consideration of temperature, humidity, and vibration, to further evaluate the system performance. Deep learning will be considered for post-processing to enhance the system evaluation accuracy and reliability.