*Review Article*

# Ultrasonic Guided-Waves Sensors and Integrated Structural Health Monitoring Systems for Impact Detection and Localization: A Review

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**Abstract:**

In the last decade the research concerning Structural Health Monitoring (SHM) systems have continuously investigated toward autonomous systems based on sensor networks. The different functional blocks of these systems are described introducing first the basic concepts for the impact detection applications based on piezoelectric sensors for ultrasonic guided Lamb waves generated into planar structures. Then the paper will review the recent progresses of the research with focus on the integration of sensors with the electronic interface, including the embedding of sensors with the structure that is represented by the smart-skin concept. The latter benefits of the advancement in piezoelectric MEMS sensors with small footprint mounted on flexible substrates. This new layout of sensors is essential for the system design based on a network of sensors nodes with real time signal acquisition capability for impact event capture. The options of a wired or wireless sensors network are also discussed for different dimensions of the monitored structure. The multifunctional sensors capability is also a new feature discussed in the paper for sensing the environmental

conditions that affect the Lamb wave signals interpretation. The power supply by environmental energy of an autonomous sensor node is another research field where large innovation is occurred and a review of energy harvesting devices is reported. The embedded signal processing capabilities in a node with IoT based wireless sensors networks, is an important fertilization between different disciplines and examples of SHM system tested in real-life application are discussed. Finally, the large capacity of data transfer of sensors networks toward large storage data archives also with low power WiFi protocols is the new frontier for exploring artificial intelligence and machine learning applied to big data and the recent research outcomes for impact detection and characterization in complex structures are reported.

**Keywords**: structural health monitoring (SHM); acoustic emission, guided waves, Lamb waves, sensors, ultrasound, piezoelectric, composites, piezopolymers, PVDF, interdigital transducer (IDT), PWAS, C-MUT, CMUT, mems, analog electronic front end; analog signal processing, impact localization, impact detection, sensor node, wireless sensor networks (WSN), IoT, aerospace, automotive, infrastructure, condition monitoring.

### Introduction

Ultrasonic non-destructive investigation (NDI) methods based on the principle of acoustic emission (AE) have evolved over the past two decades towards structural monitoring systems with guided ultrasonic waves **[1,2]**, driven by applications in the aerospace, civil engineering, energy conversion and transportation systems automotive (e.g. wind turbines, pipelines, liquid natural gas cylinders). The safety of the structure and the prediction of life or maintenance are the key elements that must be provided by SHM systems and the main concept behind were explained in a comprehensive work by Farrar and Worden **[3]** and in a related book **[4]**. Breakages due to fatigue due to defects, mechanical and thermal stresses, impacts with objects, etc. are all possible causes of damaging. The damages are sometimes

not visible because it is internal to the structure or small but not without importance from the point of view of the safety and reliability of the operation of the system. To avoid catastrophic accidents the damage prognosis is an essential task connected to the impact events; a framework for the damage prognosis was described in chapter 14 of the book published by Farrar and Worden **[5]**.

SHM, unlike Non-Destructive Testing (NDT), requires the installation of sensors/transducers operating in the environment in which the structure operates under remote control and for this reason the realization of such systems requires a considerable effort of integration of several disciplines:

(1) modelling of damage physical phenomena and their influence on the physical sensed quantities,

(2) sensors including calibration and self-diagnostics,

(3) front-end electronics including embedded processing,

(4) data transmission (wired, wireless),

(5) online (or real time) or offline signal/image processing,

(6) impact event detection and localization

(7) damage detection and classification techniques based on database processing,

(8) prognostics,

(9) artificial intelligence/machine learning for automatic damage detection and progression

evaluation.
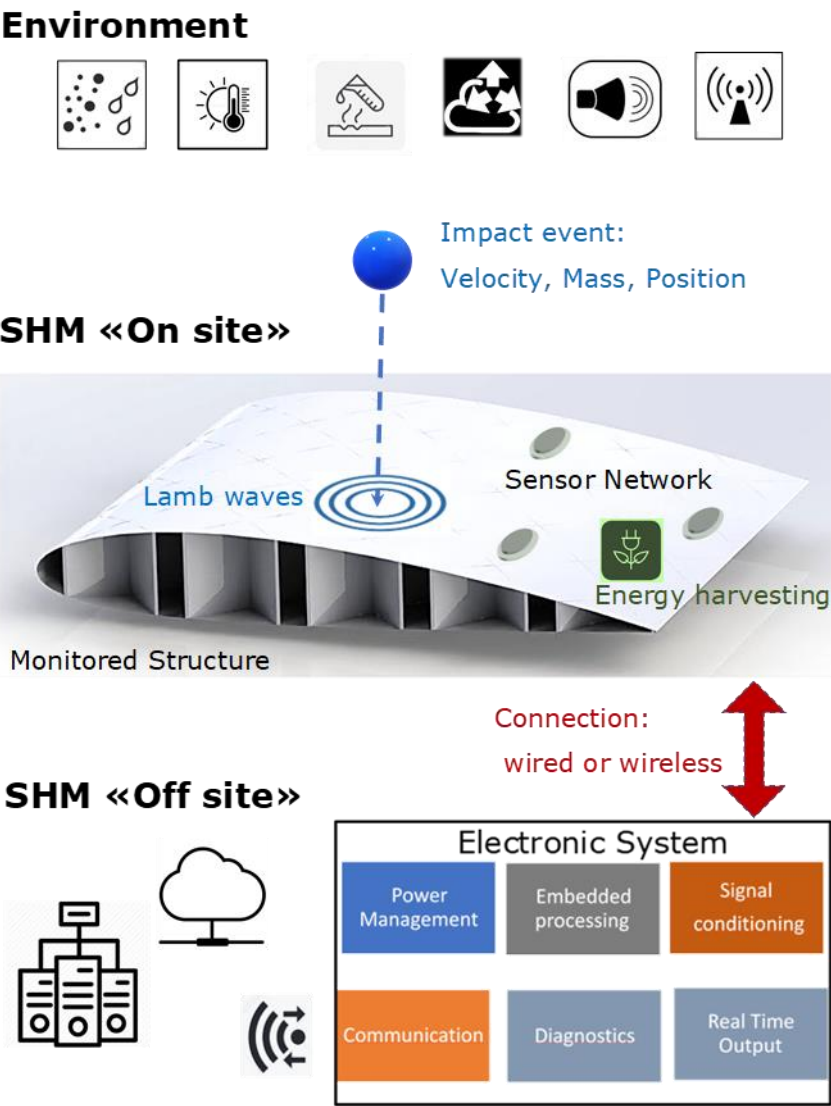
Figure 1 Graphical representation of an advanced SHM system for impact monitoring. (Top) Environmental conditions (dust, moisture, temperature, pressure, vibrations, electromagnetic interference) and impact events characterized by the object mass, velocity, shape and dimensions. (Centre) On-site components of the SHM system subjected to environment conditions installed on the monitored structure (e.g. a section of a composite airplane wing). (Bottom) Off-site components installed remotely and connected to the sensors network; the Electronic System can operate in a protected environment (e.g. inside airplane fuselage) with real-time processing capability. Off-line signal/data processing based on big data archive with workstations connected to the web for software applications of AI/ML and prognostics.

Following this list, in Figure 1 are illustrated the different sections of an SHM system and

their interaction: the environmental conditions, the on-site hardware and the off-site

hardware and software resources. The different characteristics of the structures (dimensions, materials, environmental conditions) and their structural monitoring systems (cost, footprint, weight, power consumption, safety and reliability criteria, response/update times) often require the design of ad hoc systems by exploiting multidisciplinary knowledge in electronics, informatics, telecommunications, and finally material technology and mechanical properties.

For a general understanding of the state of the art, the reader can refer to the review paper of Mitra et al. **[6]**, where several publications relating to the various components of an SHM system are discussed (see above list of points (1)-(9)). In that paper are considered the various monitoring techniques based on UGW piezoelectric and fiber optic sensors, laser vibrometry techniques and others. In addition, indications are given of what research and development lines may be for advanced SHM systems. As already introduced in this paragraph, monitoring techniques based on ultrasonic guided waves (UGW) by piezoelectric transducers are among the most common and most developed since they have a longer history **[7]** than SHM systems based on optical sensors, in particular Fiber Bragg Grating (FBG) sensors; for completeness the evolution of state of the art for optoelectronic sensors is reported in **[8–12]** but is not discussed further in this paper. Similarly, the evolution of piezoelectric materials for the realization of sensors and actuators of UGW, the development of integrated electronic components and systems with low power consumption, makes it necessary a continuous updating of the research to provide possible design methodologies, technologies, to bring SHM systems increasingly widespread and tested in the field. Although many published papers report the outcomes obtained with

laboratory set-up of guided ultrasonic wave SHM systems, their demonstration in the field is still limited. For the latter problem, there are various reasons but certainly one of these is the complexity of the installation of the sensors on a target structure, the real time signal acquisition and processing and the replication of the real-life environmental conditions. An interesting  reference for the testing of SHM systems in the aerospace industry is provided in a report presented by Dennis Roach of Sandia National Labs **[13]**: this report shows the objectives and implementations of SHM systems for airplanes and includes several examples with piezoelectric and fiber optic sensor applications for monitoring impacts, deformations, debonding, delaminations and damage progression.

Finally, it is useful to point out the effort made to create standards for the development of systems and methods for SHM and NDT based on acoustic emission, especially for the rapidly evolving SHM sector  and for example the British Standard for Acoustic Emission and Condition Monitoring can be found in The Official Yearbook of the British Institute of Non-Destructive Testing **[14]**.

After this introduction of the background of SHM systems based on UGW in active and passive modes, the present paper focuses the elements of the system shown in Figure 1 for the implementation of impact monitoring advanced systems on metal and composite materials with UGW piezoelectric sensors. In this paper we consider primarily piezoelectric sensors used for impact detection in passive ("listening") mode but also in combination with the transducers operating in active mode for the investigation of damage and its progression over time. The trend of integrating different sensors types (UGW, FBG, accelerometer,

strain, temperature, etc.) into a node increases the information about the impact and the operational conditions of the sensors that are influenced by the environment leading to the concept of a "multifunctional sensor node".

The evolution from the common AE monitoring configuration with a layout of sparse single element sensors with off-the shelf electronics to the recent design of sensors networks with "smart-sensor nodes", requires a continuous analysis and evaluation of the progresses in several fields.

This work first presents a review of methodological developments about the criteria to be adopted for the elaboration of impact-generated Lamb wave modes (Section 1). Then, it addresses technological developments about UGW sensors and actuators including new materials and sensor types with a focus on microfabrication technologies (Section 2), front-end analog-digital electronics and power management (Section 3) and the integration wired or wireless sensor networks (WSN) with real-time acquisition and signal processing capabilities for monitoring environmental parameters (Section 4). Finally, the authors believe relevant to report in Section 5 the recent applications of Artificial Intelligence (AI) and Machine Learning (ML) for autonomous detection and positioning of impact events. In the Conclusions, we will draw guidance on research topics and challenges in the various areas covered by sections 1 to 5. To ease the reader interested in selected topics tackled in this paper, an acronym list is reported in Appendix A; the list also shows acronyms that are recently introduced in the literature by new technologies and methodologies adopted in this multidisciplinary field and the reader can familiarized with.

1.  **Characteristics of signals generated by impacts on planar structures relevant to the design of SHM systems.**

**1.1 Dispersion and attenuation of Lamb waves.**

In this section are discussed the implication of the attenuation and dispersion characteristics of UGW relevant for the design and implementation of a SHM system. The interested reader can find main references for the theory and modeling of ultrasonic guided waves **[1]** and **[15]**. Briefly and without pretense of theoretical rigor, we remember that ultrasonic waves guided for SHM, are mechanical waves that propagate within a material delimited by an interface with a different medium. Propagation within the space-limited structure simultaneously produces dispersive modes of propagation in frequency. In the case of structures with thicknesses comparable to wavelength, such as thin planar structures, propagation modes have symmetrical and antisymmetric characteristics with respect to the axis of symmetry of the structure and are determined by the theory behind Lamb waves, as explained in **[16]**. For an isotropic and homogeneous laminate material as aluminum, we illustrate the dispersion characteristics in **Figure 2** by the calculated phase velocities for the different guided modes versus the *frequency x thickness* product (*fxd*).
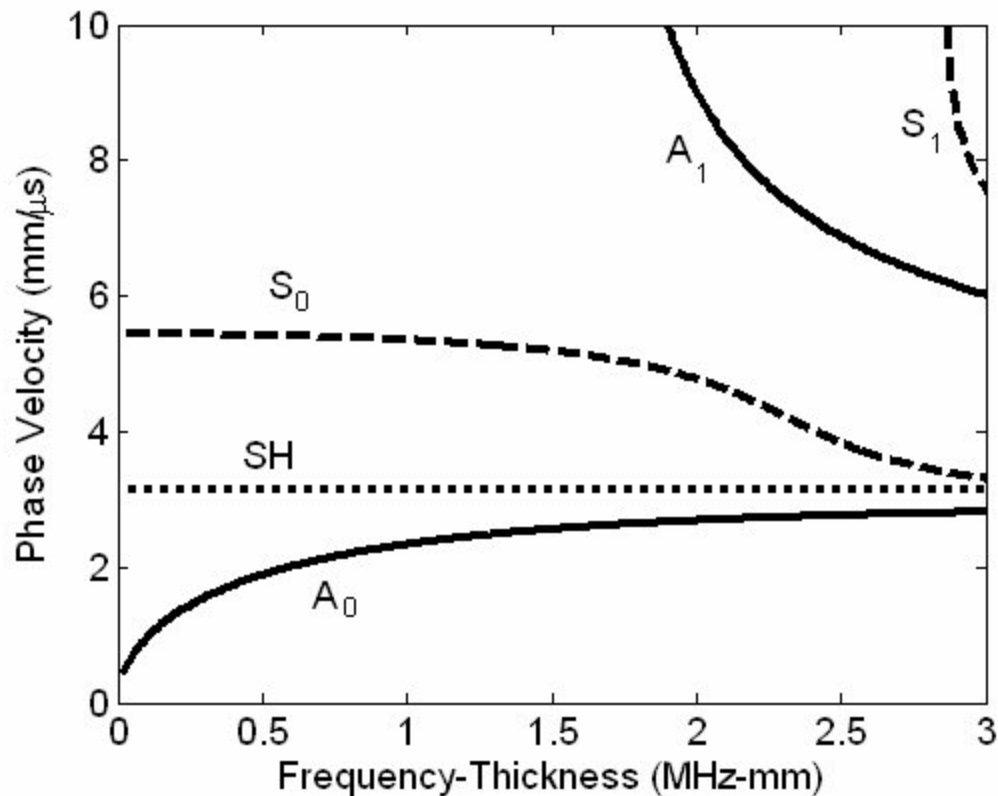
Figure 2 - Dispersion curves of phase velocity for low order modes Symmetric ($S_0$) , Antisymmetric ($A_0$) and Shear Horizontal (SH) in an aluminum plate. The diagram shows that higher order modes ($A_1$, $S_1$, etc.) are generated above the cut-off value of 1.5MHz x mm.

The propagation of symmetrical modes within a planar structure is therefore a two-dimensional phenomenon; the propagation of the various modes is subjected to attenuation that mainly follows the law of geometric decay inversely at the root of the distance. Author in [15] proposed a deep and comprehensive analysis of the attenuation phenomena that are basic to differentiate the design of SHM systems according to the characteristics of the different materials (composite or metallic) and the size of the structure; thus attenuation analysis is essential to define the distance and area coverage with a certain type of transducer/sensor without exceeding the attenuation limit (50-70 dB), that results difficult to deal with  analog-front-end (AFE) electronic based on off-the-shelf components, unless acceptable expensive and complex electronic customized design. Indicatively, the operating

frequencies for Lamb's guided ultrasonic waves range from 100 kHz to 1 MHz, and in this wide range a compromise must be found between attenuation, wavelength, minimum detectable impact energy, and for the transducers/sensors the size, type, sensitivity and bandwidth. To solve these problems, methods for optimizing the position of transducers have recently been proposed by Mallardo et al. **[17]** based on the background of UGW propagation theory; in this work a method is developed to define the optimal positions considering the characteristics of the material and sensors thus also optimizing the number of sensors transducers, while concluding that there is no general solution to the problem since each application has different constraints and therefore requires a series of a priori choices.

**1.2. - Ultrasonic guided waves generated by different velocity of impacts on isotropic elastic plates.**

Impact monitoring systems can be designed for different applications where impacts with different objects hitting the structure have different energy, mass, velocity. It is of interest to explain the different effects on UGWs generated by impacts at different velocity. There are several categories of impact loading: low velocity (large mass), intermediate velocity, high/ballistic velocity (small mass), and hyper velocity impacts. These categories of impact loading are important because there are remarkable differences in energy transfer between the object and target, energy dissipation and damage propagation mechanisms as the velocity of the object varies. According to the literature, low velocity impacts occur typically at a velocity below 10 m/s, intermediate impacts occur between 10 m/s and 50 m/s, high velocity (ballistic) impacts have a range of velocity from 50 m/s to 1000 m/s, and hyper velocity impacts have the range of 2 km/s to 5 km/s *[18]*.

The study of impacts that occur in an isotropic elastic flat plate is based on following assumptions:

- The ultrasonic signal generated by an impact is a guided wave signal that propagates into the plate without energy loss *[19,20]*.

- The frequency content of the ultrasonic signals generated by impacts depends on the impact velocity *[21] [22]* and is not modified during the propagation inside the plate *[23]*.

According to the above assumptions we can remark that the main feature of the signals generated by impacts is the impact velocity that also determines the amplitude of the Lamb waves. The impact velocity $v_i$ can be calculated by knowing the kinetic energy $E_k$ and the mass $m$ of the impacting object as reported in the following formula:

$$v_i = \sqrt{\frac{2E_k}{m}}$$

(1)

The study reported in *[22]* shows that two fundamental propagation modes can be distinguished in impact phenomena: a slow propagation mode (flexural mode or $A_0$ mode) and a fast propagation mode (extensional mode or $S_0$ mode). The amplitude of the $A_0$ mode signal is dominant respect to the $S_0$ mode but the amplitude of the $S_0$ mode signal can be much significative based on the impact velocity: the higher the impact speed is and, on the consequent, higher is the amplitude of the signal relative to the $S_0$ mode.

Authors in *[22]* also reported an acquired signal from a high-speed impact (700m/s) where they demonstrate that applying a low-pass filter with (with a cut-off frequency of 800kHz),

it is possible to extract only the two fundamental propagation modes ($A_0$ and $S_0$) and in this case the amplitude of the $S_0$ mode becomes comparable to that of the $A_0$ mode. According to the author experience, we investigated the possibility to extrapolate the $S_0$ mode signal also in low velocity impacts by applying a low-pass filter in the analogic front-end electronic board with proper cut-off frequency. Figure 3 shows ultrasonic signals generated by a low-velocity impact (about 3m/s) on an aluminum plate with thickness 1.5 mm.
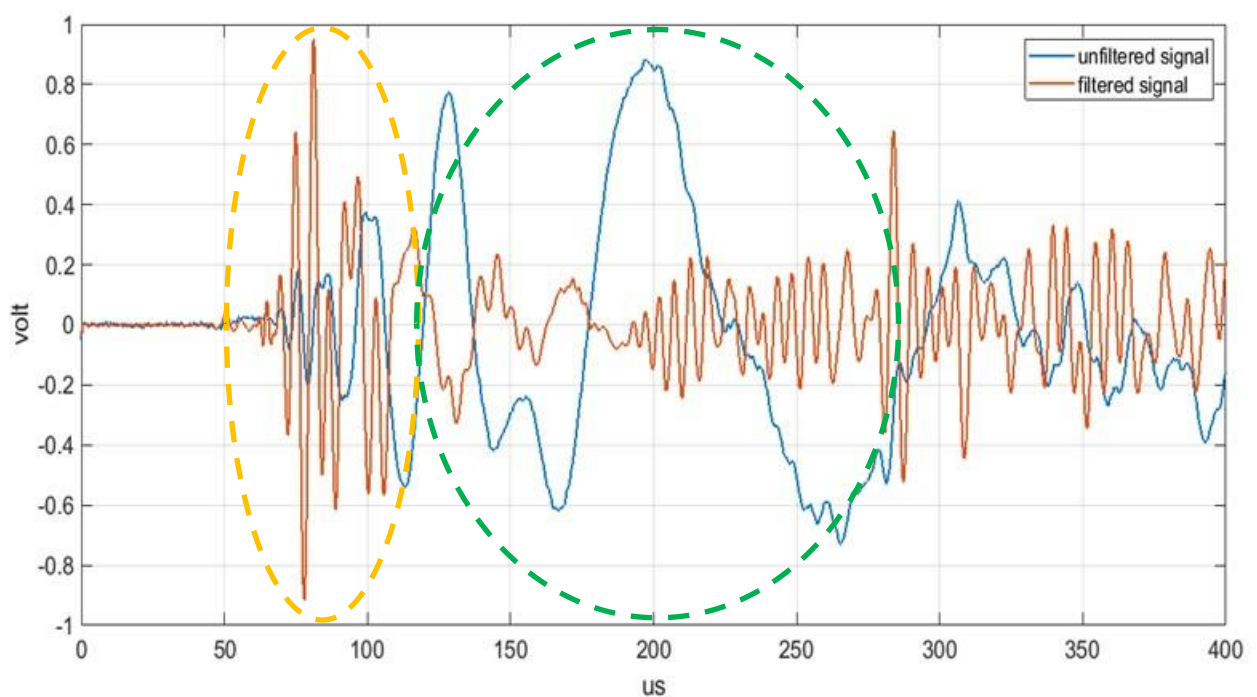
Figure 3 Ultrasonic signals generated by a low-velocity impact (about 3m/s) in blue color and the same signal filtered by an analogic low-pass filter with a cut-off frequency of 400kHz in red color. The dotted green circle represents the portion of the signal relative to the $A_0$ mode; the dotted yellow circle represents the portion of the signal relative to the $S_0$ mode.

From the analysis of Figure 3 it is apparent that the fast propagation mode $S_0$ become comparable in amplitude with the $A_0$ mode only after filtering the ultrasonic propagating signal generated by the impact. The possibility to process the fast $S_0$ mode instead of the slower $A_0$ mode, is often the best signal processing design strategy, because this early arrival time signal is less affected by overlapping of the multiple reflections from the structure edges [24]; moreover, the impact signal detection and positioning is even more complicated

in large structures for the higher attenuation and the mode conversions after the propagation on areas with different thicknesses. The topics briefly reviewed in this section remarks the importance of the understanding the physical background for designing sensors and the analog front-end to simplify and make reliable the information extraction from the signal.

### 1.3 - Signal processing techniques for dispersion and environmental factors compensation.

From the preliminary considerations in the Introduction, we can remark that the rapid evolution towards integrated SHM systems operating in different environmental conditions follows a different path than common AE and NDT techniques, that use volumetric longitudinal or transverse ultrasonic waves with piezoelectric transducers connected to portable instruments and the region of interest (ROI) manually scanned of by a trained operator; main differences are found for the signal processing adopted both for passive and active mode operation of the SHM system. The analysis of information gathered by a sensors layout due to the interaction between the UGW dispersive modes and the various types of structures is certainly a challenging aspect from the point of view of signal processing techniques that are based in a widespread way on the wavelet frequency time (CWT) or the Short Time Fourier transform (STFT). However, simple analysis with CWT or STFT may still be too restrictive in the presence of structures with inserts, reinforcement elements and therefore recently several methods have been proposed to overcome this problem, such as reported in [25–27]. Another important method introduced in [28] to compensate for the dispersion and alleviate the complexity of Lamb wave signal interpretation, is the well-

known time-reversal approach; this approach was adopted by Zeng et al [29]. UGWs used in active mode for damage assessment have a great sensitivity to detect internal damages into the structure and this is one of the main reasons of successful application of this NDT technique. The detection is often implemented on a data driven approach, where received UGWs from a sensor layout is compared with a baseline of data acquired with a pristine structure. This approach is rather simple to be implemented also in sensors with on board embedded processing, but it suffers from the sensitivity to environmental and operational conditions, mainly temperature variations. Recently, Mariani et al **[29,30]** have proposed a method for the compensation of this detrimental phenomenon. For the electro-mechanical-impedance (EMI) method, the temperature compensation was achieved with some benefits by using ANN as reported by Sepehry et al **[31]**.

### 1.4 - Advanced methods for impact detection and localization.

In general impacts on a thin planar structure generate guided waves modes that can propagate away from the impact point. The localization of the impact point is commonly achieved by adopting a triangulation algorithm with at least three passive ultrasonic sensors deployed on the planar structure. The accuracy of the impact point estimation depends on the estimates of the guided modes velocity and the measured differential time of arrival (DToA) among the sensors. Recently several papers have been published to improve the reliability and accuracy of impacts on complex structures other than from the simple panels often used by researchers in laboratory for calibration and performance assessment of a SHM system. The Akaike Information Criterion (AIC) criterion for the accurate estimation of DToA has been demonstrated by De Simone et al *[32]*. Further research work has

consolidated the investigation of the advantages of AIC and a modified version for impact monitoring has been recently proposed by Seno et al *[33]*. In the latter work an ANN was trained for automatic classification of defects in composite materials tested in laboratory and in simulated operational conditions. As already reported in the Introduction an extensive review of AE physical parameters for SHM systems is reported by Ono in *[15]*. The characteristic of UGW generated by impacts have been outlined in sections 1.1 and 1.2. Such guided wave modes propagating into the planar structure mix-up due to the phase velocity dispersion and in addition the reflection phenomenon from the edge or from inserts or stiffening material or defects *[34]*. Moreover, mode conversion can occur when the ultrasonic guided waves travel across a discontinuity of acoustic properties in the planar structure, for example a change in thickness or material composition. In general, the wave shape of the impact generated UGW is complex but a list of features supported by theoretical modeling developed by Hakoda et al *[35]* based on the phase velocity analysis can be derived. It is worth to observe that the propagation velocity analysis in general is more complex for composite structure respect to the simple case shown in Figure 2; even the example of time domain signals generated on an aluminum plate reported in Figure 3 is a simplified scenario respect to real-life cases. In the following we report two main considerations that are starting guidelines for the impact signals processing:

1) the early part of the signal consists of the fast phase velocity modes, typically the $S_0$ mode in the low frequency range below the cut off *frequency x thickness* product (e.g. equal to 1.5 MHz x mm in *Figure 2*).

2) in the later part of the signal the contribution comes from slower modes that show also dispersion effect as for the $A_0$ mode *[36]* or signals that traveled along longer paths or multiple reflections.

We can observe that $S_0$ mode being faster it is less prone to be hidden by the other signals but has a lower amplitude as its attenuation is higher than $A_0$ mode; the higher velocity of this mode implies also that the error on its DToA estimation causes higher spatial errors in the triangulation algorithms or any other positioning method based on DToA *[37–39]*. The theory of UGW in a plate like structure considers also other type of waves than Symmetrical and Antisymmetrical Lamb wave modes: the shear horizontal (SH) mode. This is a non-dispersive mode and piezoelectric sensors/transducers can be designed to convert this wave type into voltage signals. Ren and Lisseden *[40]* have demonstrated capability of sensing also Lamb waves that are of interest for impact detection in passive mode. Altammar et al *[41]* studied the actuation and reception of shear modes by exploiting the $d_{35}$ piezoelectric coefficient of PZT sensors embedded in a laminate structure.

**1.4.1 - Advanced signal processing techniques for anisotropic plate-like materials.**

Anysotropic characteristics of composite structure require the adaption of impact positioning algorithm developed for isotropic plate like materials. The early research on signal processing techniques for isotropic metallic plates and anisotropic composites can be found in *[39,42–44]*. More recently the signal processing techniques have been progressed to account for the UGW dispersion (see section 1.1) and anisotropy of different type of composites like unidirectional, quasi-isotropic CFRP and honeycomb, of interest for aerospace industry *[32,39,45–47]*. An early work of Scholey and Wilcox in 2010 *[48]*,

addressed the problem of impact detection on 3D structures and recently Moron et al in 2015 *[49]*. Lanza di Scalea et al. published a work *[50]* for impact monitoring in complex composite material structure with an algorithm based on the rosette sensor configuration; this model-based approach could solve the problem of variation of phase velocity along different direction of a composite material.

**2. Sensors and transducers for impact monitoring**

Piezoelectric sensors are common devices for the passive detection of impacts on the structure. However, an SHM system can also operate in active mode with piezoelectric transducers for generating UGW for damage evaluation because of impact events. In this way there is an interest to have a dual use of the transducers both for passive and active operation with an advantage on the reduction of system complexity. In this section we will revise the main characteristic of sensors and some considerations how to use transducers in passive mode are reported.

**2.1 Single element piezoelectric sensors for impact detection and emerging/new sensing materials.**

The piezoelectric sensors commonly used for reproducing the impact stress waves in passive mode are typically based on PZT, $BaTiO_3$ or PVDF piezoelectric materials [7,22,51–57]. According to the choice of piezoelectric material, the sensor design or selection is completed by the definition of the fabrication technology and the dimension/shape that must accomplish to several system level target parameters such as:

1. Bandwidth

2. Sensitivity /Gain /signal to noise ratio (SNR)

3.      Input Impedance

4.      Dynamic

5.      Temperature range

6.      Mechanical features: Stress / Strain / Brittleness / Flexible /Stretchable

7.      Bonding / Embedding

8.      Electrical connection/wiring

9.      Cost

Typically, single element sensors have planar dimensions in the order of several millimeters and operate in non-resonant mode; these conditions lead to an almost isotropic (omnidirectional) sensitivity to UGW and broadband frequency response (e.g. 20 kHz – 1MHz), so that are versatile sensors for many applications as they cover a large range of the *fxd* product of the phase velocity diagram (see section 1.1). On the contrary these broadband sensors are not UGW mode selective and as pointed out in section 1, the overlapping of different modes requires clever signal processing to extract information on impact position. For example, a comparison of different type of sensors can be made observing three different and common sensors technology for UGW detection (see Figure 4). By comparison, the electrical, mechanical, and piezoelectric characteristics of these three types of materials it is quite straightforward that for each application we can select the most appropriate sensor technology.

The characteristics of these three sensors shown in Figure 4 are reported in Table 1.
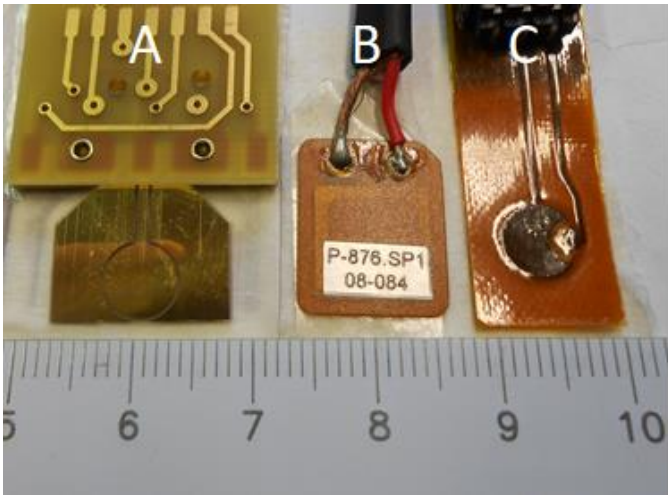
Figure 4 Example of three different type of piezoelectric sensor for SHM: (A) circular PVDF sensor made with bioriented PVDF film furnished by Precision Acoustics, (B) BaTiO$_3$ piezocomposite, model DuraAct produced by Physik Instrumente, (C) PWAS, model SML-SP produced by Acellent.

Table 1 Characteristics of single element piezoelectric sensors.

| Type | A | B | C |
|---|---|---|---|
| Model | Circular_PVDF | P-876.SP1 DuraAct | SML-SP-1/4-0 |
| Manufacturer | By authors (Precision Acoustics material) | Physik Instrumente | Acellent |
| Capacitance | 86pF | 8nF +/-20% | 1.1nF |
| Thickness piezoelectric element[µm] | 110 | 200 | 140 |
| Material | Piezo-polymer | Piezo-ceramic | Piezo-ceramic |
| Shape | Circular | Rectangular | Circular |
| Dimensions [mm] | 6 | 16x13 | 6 |
| Operation temperature Range | -80 °C, +50 °C | -20 °C, +150 °C | -40°C, +105 °C |
| Acoustic Impedance [MRayl] | 2.7 | 30 | 33 |

By the analysis of Table 1 for three sensors having comparable area, it can be pointed out

the difference in capacitance that is a relevant parameters for the electronic design (see

Section 3) and the acoustic properties made clear the different performance for the acoustic matching with different materials like metal or CFRP that influence the sensor sensitivity; while piezoceramic material are well matched with metals , piezocomposite and piezopolymers are better suited for plastic composites.

In the literature are reported several types of commercial and customized sensors that can be compared according to the set of parameters listed above (1 – 9). For example, Wu et al. [53] compared the commercial Accellent Smart Layer® sensors arranged in a SMART Layer (SL) with PZT flexible transducers fabricated with sol-gel process in order to achieve a large bandwidth for inspection of materials with large thickness with surface waves (3-6MHz) or for NDI of small *kxd* products of laminate materials with UGW (300-600 kHz). An interesting publication about the state of art for in service application of commercial transducers for SHM in aerostructures is available at https://www.compositesworld.com/articles/structural-health-monitoring-ndt-integrated-aerostructures-enter-service.

Qi et al. [58] compared PVDF film and PZT patch sensors for impact monitoring of low velocity impacts in smart aggregates and the conclusive remarks is that there are relative merits for both materials. Jia [59] analyzed the dynamic response of embedded PVDF sensors at different impact velocity (see section 1.2).

Recently the research is moving toward new sensors and there are important novelties in the research of functional materials with enhanced piezoelectric properties: an example published recently by Han et al [60] is the development of highly sensitive impact sensor

based on a PVDF-TrFE/Nano-ZnO composite thin film. The percentage of doping of PVDF TrFe Copolymer with ZnO increases the sensor sensitivity and the dielectric constant. That paper reports also preliminary results on signal acquisition for different impacts. Another approach was proposed by Capsal et al [61] by the technology development of a flexible, light weight and low-cost electroactive coating obtained by the dispersion of $BaTiO_3$ submicron particles on a in a polyurethane matrix; the experimental set up was demonstrated to detect impacts on an aircraft structure in real time. Finally, a recent study on piezoresistive properties of SiC has been published by Kwon et al [62]: a SiC fiber sensor network has been embedded in a composite structure for low-velocity impact localization on a composite structure. The SiC fibers have potential to reduce the mechanical discontinuities introduced by the sensing elements that is a critical point for the embedment of many types of piezoelectric elements. Another innovative approach introduced in [63] is the adoption of nanotechnologies for embedding carbon nanotubes (CNT) into composite materials and the analysis of electrical resistance variation for high and low energy impacts is shown. The introduction of new materials for sensing impacts and damage monitoring is a new fertile field for the research and the advantages and disadvantages respect to common piezoelectric sensors will be clear when such devices will be more mature by moving from laboratory to real-field tests.

### 2.2 Multifunctional sensors based on piezopolymer film material.

The possibility of using the same device operating in passive mode for impact monitoring and for damage detection and localization in active mode, is an important advantage to simplify the SHM system complexity. Moreover, added sensing capabilities to the same

device as temperature or strain measurements, lead to a new type of devices that are called "multifunctional" sensors. For example, the data obtained from these devices are usefully processed by clever algorithms to compensate for variation of the UGW propagation and physical sensor properties due to thermal drift (see section 1.3). In addition, the UGW mode selection for the damage evaluation is another useful requirement to have in a transducer. In this section we will explore the concept of a multifunctional sensor based on interdigital transducers (IDTs). IDTs for guided Lamb wave offer the advantage over single element transducers (see Figure 4 ) of the selection of Lamb wave mode for a given material by the definition of the $kxd$ product (see Figure 2); in this regard they can be considered as narrow band devices. IDTs for guided Lamb wave applications are created by a sheet (or thin plate) of piezoelectric material equipped with electrodes on the opposite surfaces: at least one side must host two sets of interleaved comb electrodes with separate connections, while the other may present a ground plane, another pattern of electrodes. A common exploded view of an IDT is shown in Figure 5, where the geometrical parameters are also defined. The transducer has one side coupled to the ultrasonic wave guiding medium (a plate-like structure). The two sets of comb electrodes are generally assumed to operate with 180°-out-of-phase signals (both in transmission and reception), such that the transducer provides geometrical wavelength selectivity when attached to the surface of a plate-like waveguide. The IDTs made by piezopolymer film like PVDF, have a unique advantage respect to ceramic of flexibility and conformability to non-planar surfaces but, according to Table 1, their limits on the temperature range as well as different sensitivity must be well understood and investigation results are reported in the following sections.
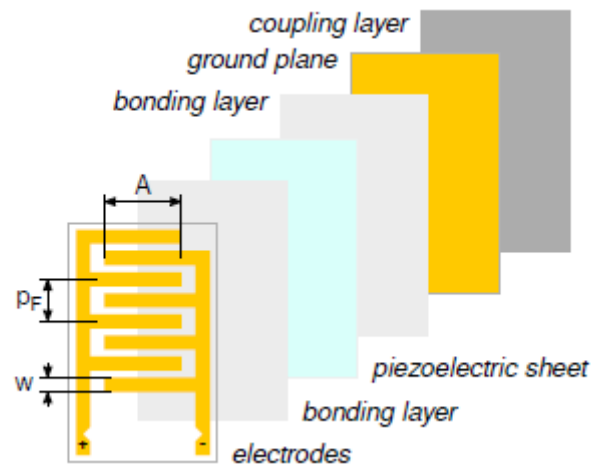
Figure 5 - Exploded view of an interdigital transducer assembly. "A" is the length of the electrodes (fingers), "p$_F$" is the finger pitch and "w" is the finger width.

IDTs developed by our group present a difference with those published by other research teams in that they are manufactured via laser etching, starting from metal-coated—usually with Pt-Au, or Cr-Au alloys—poled PVDF sheets. Since PVDF is mostly transparent to the laser beam, it does not heat up considerably during the etching process, and the laser passes through the polymer etching the back-side metallization as well. Therefore, the process results in having an identical electrode pattern on both sides of the PVDF.

The possibility to ablate with a quick process (tenth of seconds) an arbitrary pattern on the metal coating of the piezo-polymer film by laser ablation, constituted an enabling technology for including different sensing elements on the same film and reduce the production costs of multifunctional sensors.

For this purpose, two additional sensory patterns have been etched alongside the IDT electrodes on the same piezo-polymer film device: a 1/4" circular element (impact passive sensor), and a resistive temperature device (RTD). The picture reported in Figure 6

illustrates the three patterns for the multifunctional sensor alongside the dimensional

drawing.
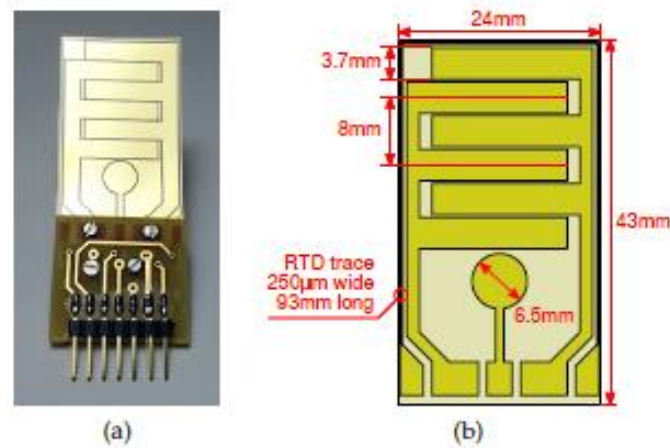
Figure 6 (a) Multifunctional sensor: IDT for active mode, circular sensor for impact sensing, RTD for temperature monitoring; (b) dimensional drawing of the fabricated device by laser ablation of the metallization.

### 2.*3* Comparison of piezoelectric PVDF and PZT sensors sensitivity for impact detection.

In the previous section is reported the design and fabrication of a circular sensor integrated

in the same IDT device with the aim to capture impact generated Lamb wave signals

propagating from any direction respect to the sensor center. Some companies have

specialized in providing patch piezoelectric sensors with characteristics suitable for

acoustic source localization, and off the shelf devices are available from Acellent and

Physik Instrumente. Specifically, in our design the circular PVDF sensor has a diameter of

6.5 mm, similar to Acellent's SML-SP-1/4-PZT sensor (1/4", or 6.35 mm) (see Figure 4).

The sensitivity of the circular piezoelectric element as a receiver were assessed by

comparing it to a PZT device of similar active area (see Figure 4), the Physik Instrumente

P-876.SP1. These two sensors were taped side-by-side to an aluminum plate 1.2 mm thick,

with a third transducer used as transmitter and placed at distance of 200mm from both. A

Morlet wavelet centred at 250 kHz was transmitted and received using the same pre-amplifier for both sensors: an instrumentation amplifier providing a voltage gain of 78 dB @ 250kHz. The excitation wavelet and the acquired traces are plotted in Figure 7(a) and 7(b) respectively.
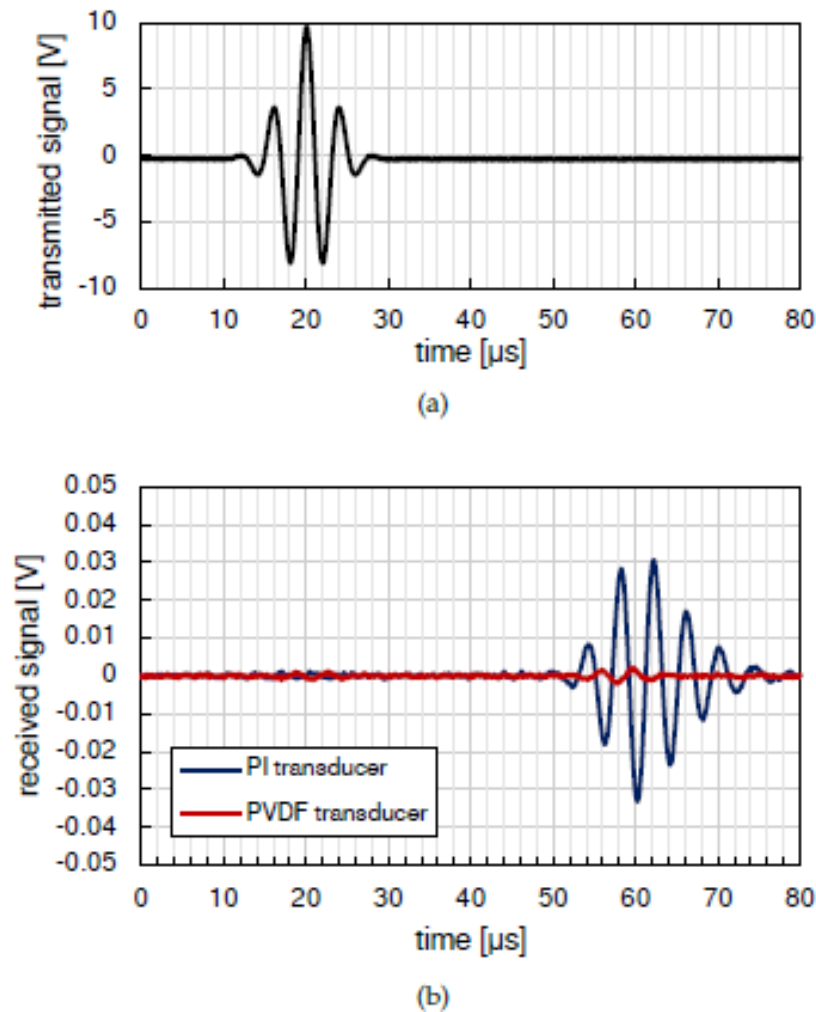
Figure 7 Experimental sensitivity comparison of the circular element with a commercial PZT sensor of same class: (a) transmitted Morlet with central frequency 250 kHz; (b) signals received from the two sensors (PI blue color and PVDF red color).

The plot shows that, as expected from the piezoelectric properties of the materials, the circular element sensitivity is lower than the PZT device. Such a wide difference, however, may not be a problem in impact detection applications, where signals tend to be rather large as reported in [59] for different impact velocities. In some cases, the large input

voltage at the preamplifier input exceeds the rail-to-rail input and saturate the output with consequent loss of information of the impact event. In conclusion the different sensitivity of the two piezoelectric materials is not a limiting factor for the choice between the two. There are other differences between that must be considered for the choice of the sensor technology as temperature. In the following section we analyze the operating temperature range of PVDF piezo films, being limited respect piezoceramic and piezocomposites (see Table 1).

### 2.4 Operating temperature range estimation of piezopolymer sensors.

In this section we report the assessment of the temperature operational limits of the PVDF material for considering their use in harsh environments (e.g. aerospace). The authors carried out some measurements at cryogenic temperatures (up to -80°C) and at high temperatures (up to +50°C) using a piezopolymer sensor pair in pitch-catch mode, realized with P(VDF-TrFE) copolymer film.

A series of cryogenic treatment tests of the P(VDF-TrFE) film sensors were conducted at the following temperatures: -20°C, -40°C, -60°C, -80°C. At first, we attached a sensor pair to an aluminum laminate with a bi-adhesive tape at a certain distance in a pitch-catch configuration and we recorded the ultrasonic signal collected to the receiver transducer before the treatment. Then we removed the receiver and we treated it at the cryogenic temperatures. After the treatment we repositioned the receiver on the plate and we recorded again the signal received. Comparing the collected signal to the receiver after the temperature treatments, we pointed out that no variation in terms of signal amplitude has been recorded for all cryogenic testing temperatures.

Another test has been carried out at temperatures up to +50°C by heating a pair of sensors attached with a bi-adhesive tape (furnished by Eurocel - SICAD group) to an aluminum plate in a climatic chamber for about one hour. Then we recorded the ultrasonic signal collected to the receiver transducer before the treatment and we recorded the same signal after reaching the temperature of +50°C. Again, comparing the collected signal to the receiver before and after the temperatures' treatment we pointed out that no variation in terms of signal amplitude has been recorded. After these tests we concluded that this type of material could be used certainly down to -80°C and up to +50°C without degradation in its piezoelectric properties. The thermal properties are also relevant for the permanent bonding of piezopolymer sensors on the structure by epoxies that often require curing temperature between up to 60°C.

**2.5 Advanced technologies for Piezoelectric Sensors in SHM systems**

The main piezoelectric materials analyzed in section 2.1, have been used to design different type of sensors and transducers in the last two decades with the scope to be integrated with the target structure. In this section we will review the developments of more advanced sensors and transducers designed for achieving different characteristics:

- embedded sensors with the structure.

- Lamb wave mode selection,

- array configuration

Sensors and transducers are often combined for passive and active mode operation. Leehman et al [36] reported the advantages of a piezocomposite transducer made by PZT fibers demonstrating the possibility to integrate such transducer in an aircraft wing. This early paper introduced the concept of sensor node with electronic integration and connection to a base station; a graphical description this system configuration is shown in Figure 8. The same paper also addressed the advantages and disadvantages of the removable sensors with adhesive tape bonding respect to permanently bonded sensors in composite structures; this problem is often found when a prototype system as to be tested in laboratory before to final testing on the final structure. It is worth to note that this type of sensor was also tested for impact detection based on the observation of a dispersive $A_0$ mode generated in a CFRP plate.
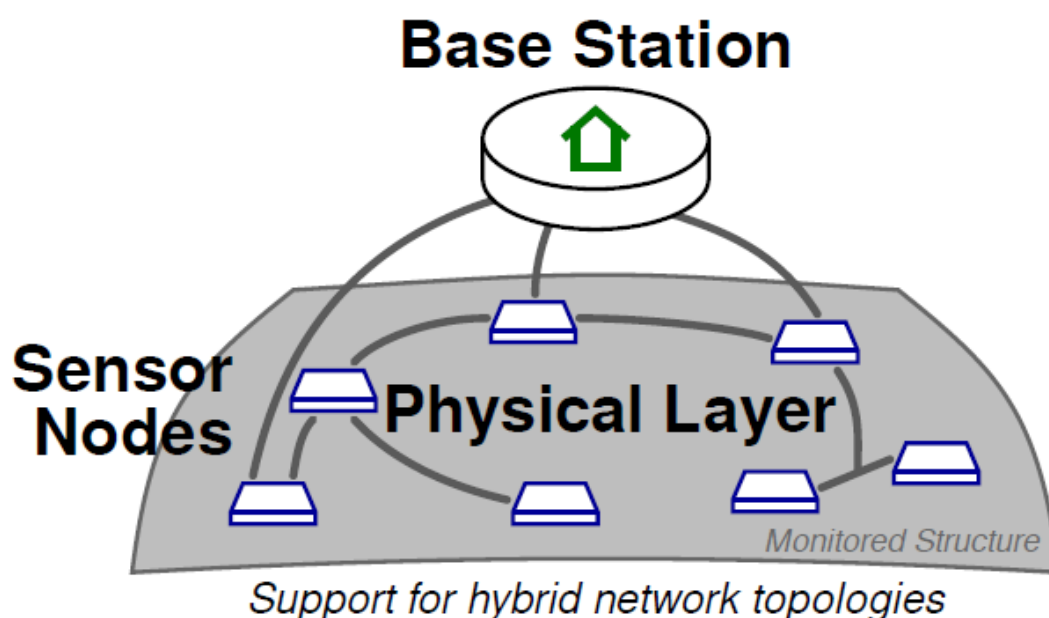
Figure 8. Graphical representation of a wired sensor network for SHM.

**2.5.1 Sensors embedding**

Another issue for sensors is the embedding in the structure to ensure durability for service in harsh environmental conditions. An example of the embedding PVDF IDTs was also carried out for composite CRFP materials by Bellan et al [64] but no easy solution for connections and wiring of the piezoelectric film was provided. Following these early works, an innovative approach based on bioinspired sensors, was proposed by Ghosal et al [65] with a ribbon of PZT element array. Recently, the concept of "smart-skin" (SS) of bioinspired embedded sensors was developed with several advantages on the installation and the simplified task for signal acquisition and processing [66]. Another interesting approach for "aircraft smart composite skin" (ASCS) was proposed in [67] with the investigation of efficient ways to connect in series and/or parallel a large number of PZT sensors with front end electronics; a signal processing strategy to convert analog information to digital sequences was also a main result towards to simplify the embedded signal processing.

Another innovation on sensor technology was stimulated by the installation of stretchable sensor networks on structures subjected by large mechanical deformation/strain under mechanical loading (e.g. COPV) [68]. The concept of flexible sensors has been further investigated in [69] with "bioinspired stretchable sensors" (BSS) with multifunctional capabilities; a screen-printed PZT technology on a substrate flexible electronics is envisaged as enabling technology for integration of SHM system with the monitored mechanical component. Another interesting review of novel EMI method for integrating piezoelectric sensors in a concrete structure or in a transportation vehicle is reported in [70]; these two different target installations both imply the operation in harsh environment;

therefore, the sensor protection by additional layer or by embedding is a key point to ensure the durability of the sensors and the system functionality. Another recent work regarding the application of stretchable sensors for AE location is proposed in by Hu et al [71] where an array of 10x10 PZT elements encapsulated in silicon elastomer layers have been developed and preliminary tests on non-planar 3D surfaces are reported.

### 2.5.2 Lamb wave mode selection

For the Lamb wave mode selection, a suitable transducer structure is the IDT as reported in section 2.2. PVDF IDT type of transducers were first proposed by Monkhouse et al [51] to generate Lamb waves in structure and following works have developed the fabrication technology Capineri et al [72], Mamishev et al [73] while the analysis of electrodes shape for tunable transducers is reported by Lissenden [40]. The latter characteristic is fundamental for the mode selection that in many cases make easier the interpretation of the signal information. An extensive review of the IDT technology is provided by Mańka et al. [74], Stepinksy et al [55] for tunable IDT realized with piezoelectric MFCs. Arrays of IDT employed in passive mode for impact detection have been experimented in an integrated SHM monitoring system for pressurized tanks by Bulletti et al [54] but the location accuracy needed was limited by the anisotropic sensitivity response of the IDT as demonstrated by Lugostova et al [75]. Moreover, the evolution of IDT used in both passive and active mode, is the array configuration where each pair of finger electrodes can be connected independently to a channel of the AFE, which allows to drive or receive signals with different time delay and gain to improve the Lamb mode selection and apply signal apodization, as shown by Bulletti et al [76].

Because the anisotropic response of the IDTs is a limiting factor when used as impact sensors, several works have investigated this design issue from the theoretical point of view Wilcox et al [77], Wang et al [78] and by experimental works, Mańka et al [79], Lugostova et al [75,80]. As shown in section 2.4, the multifunctional sensor solution with a circular piezoelectric element included in the same device with an IDT and a RTD sensor can overcome the problem of isotropic and broadband impact sensing without adding complexity and cost to the system (see Giannelli et al [81]). In this regard, a complete review of the SHM sensors technologies and systems is recently published by Qing et al [57] where a network of multifunctional sensors for environmental adaptivity is proposed: EMI, UGW, RTD and strain data can be used and correlated to minimize the influence of variable operating conditions.

The concept of UGM selection by an IDT tunable transducer have been expanded by studying different electrodes geometries like the spiral transducer developed by De Marchi et al. [82]: in that paper the synthesis of directivity is presented and can be usefully adopted for the definition of the sensors layout and number of sensors/transducers to be installed on a defined structure; moreover that paper indicates also a suitable signal processing strategy based on DTOA information for considering the spiral based patterned geometry. Other type of electrode patterning has been studied as the annular shaped IDT designed for SHM application published by Koduru et al [83] and Gao et al [84]. This solution has been recently implemented with screen printed technology by Salowitz et al [85].

### 2.5.3 Array configuration

In general sensor network are installed on the structure to have an optimal area coverage. An alternative solution is the installation of an array of transducers for implementing the scanning of the area by electronic beam steering in transmission and receiving mode. The latter is also of interests for the implementation of algorithms for the estimation of the direction of arrival of a Lamb wave generated by an acoustic source. The programmable beam direction of a transducer emission and reception can be obtained by the well-known phased array solution common in the NDT and medical ultrasound echographic instruments, equipped with integrated analog-digital electronics to achieve a real-time beam steering. Generally high spatial resolution imaging is obtained for the ROI selected on a portion of the plate-like structures, that must be reachable by a line of sight from the phased array without obstacles (inserts, stiffeners, bolts) in between. The SHM based on phased array implies higher cost, higher power consumption and is not scalable with the dimensions and shape of the structure. There are important developments recently published by Giurgiutiu et al [86] with arrays based on PWAS and more recently by Ren et al [40,87], with 16 elements PVDF arrays operating in a broad bandwidth (0.2-3MHz). An example of an embedded instrument capable to program a phased array by remote connection is the Pamela project developed by Aranguren et al [88]: an embedded electronic instrument with FPGA can be programmed for specific signal processing of data acquired by a 16 piezoelectric element phased array.

**3. Influence of front-end electronics on impact detection and localization**

In the previous sections we have described the importance of the choice for the sensor technology and configuration for passive impact sensing while in this section we will address and explain other important issues for the analog front-end design: impedance matching, input signal dynamic, bandwidth, distortion and power supply. The role of electrical impedance matching is crucial for SHM integrated system design as the operating bandwidth is continuously increasing and different type of AE sensors are in use; for this aim a recent paper has been published by Rathod et al **[89]**. Poor electronic design lead to a loss of information on the impact event as reported by Qing **[57]**, where several approaches are presented to process the signals generated by a set of sensors; other relevant works for the electronic design developments of sensors network are the Match-x project **[90]** and the work of Ferin **[91]**. A useful reference paper for AFE designers is published by Beatie **[92]**, where an analysis of important electronics characteristics of the AFE and their influence on the overall impact detection performance is reported. Today ADCs can acquire at a sampling frequency ($F_{sampl}$) of 50 MHz with 16-bit resolution and at low power with 3.3V voltage power supply. Such resolution implies a 90dB dynamic at the ADC. This large input signal dynamic range is useful to preserve signal integrity when both low and high velocity impacts must be monitored. The choice of the sampling frequency is important to avoid oversampling nuisance in automatic signal processing schemes and high data rate transmission from sensor node as noticed in the work of Ebrahimkhanlou et al **[93]**. Typically for a broadband SHM system, it is required a maximum analog bandwidth of 1MHz which lead to a minimum frequency sampling of 5MHz considering a 5-fold factor; at this sampling rate the new ADC technologies have a low power consumption.

**3.1 Programmable single channel front end electronics for signal conditioning**

In this section we will explain the advantages of designing or using a programmable electronic for interfacing piezoelectric sensors with different impedance and sensitivity and we will review the main design concepts. In Figure 9 are shown the main electronic components of a programmable single channel AFE and we include a numerical example for the evaluation of performance; the list of the main components is reported as follows:

1)  A low noise amplifier (LNA) with fixed open loop voltage gain (typically 10dB) and programmable feed-back impedance to match the sensor impedance bandwidth equal of larger than the sensor (e.g. 50kHz- 1MHz). For example, we can assume a Noise Figure (NF) better than 5 dB, input equivalent noise density 0.6 nV /√Hz.

2)  A programmable Variable Gain Amplifier (VGA) for adjusting the signal amplitude to the input voltage rail of the ADC (e.g. selectable gain -10dB, +30 dB).

3)  A passive anti-aliasing filter (AAF) with attenuation rate depending on the filter order (typically 6dB) and cut-off frequency $f_{cut-off}$ equal to the higher spectral component of the input signal.

4)  An ADC with sampling frequency $F_s$ selected according to Nyquist criterion and higher 5-20 times the $f_{cut-off}$ . The ADC should be selected with low equivalent noise floor.
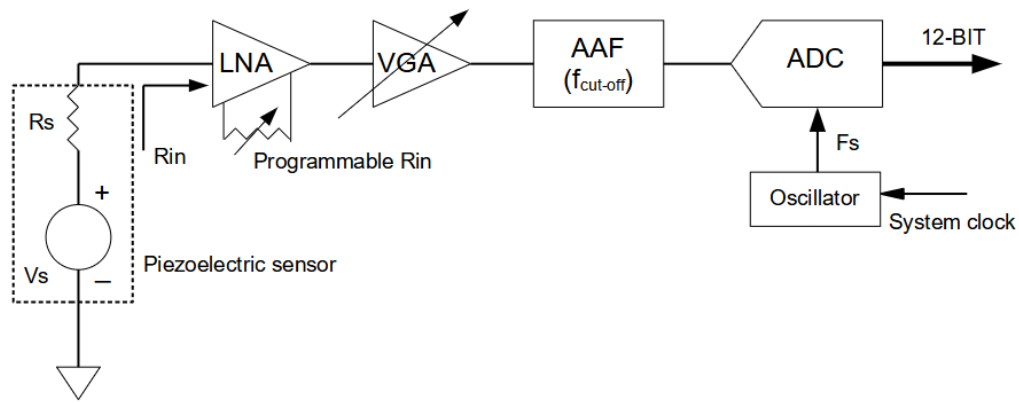
Figure 9 - Programmable single channel AFE for signal conditioning of piezoelectric sensor.

By a numerical example is here illustrated the intrinsic noise performance for this chain that allows a programmable gain of the VGA to adjust for different input signal amplitudes. The total voltage gain can be calculated with the reference component values and the max VGA gain of 30 dB:

$$A_{VTOT(dB)} = Av\,(LNA) + Av(VGA) - Av(AAF) = 10 + 30 - 6 = 34dB \text{ or about 50 V/V} \tag{2}$$

For this value considering an input dynamic of 3V dictated by the rail of power supply voltage of the ADC, we can manage a signal input generated by the sensor with voltage

$$Vs = 3V/50 = 60 \text{ mV} \tag{3}$$

Assuming an equivalent noise density for a 16bit ADC of $Vn(ADC) = 30$ nV $/\sqrt{Hz}$, we can calculate the equivalent input noise for the maximum $A_{VTOT(dB)}$ that is :

$$Vn\_in\,(ADC) = Vn(ADC) / A_{VTOT(dB)} = 30 \text{ nV} /\sqrt{Hz} / 50 = 0.59 \text{ nV} /\sqrt{Hz} \tag{4}$$

This equivalent input noise should equal or smaller than the intrinsic input noise of the LNA and in this case the criterion is satisfied being 0.6nV/$\sqrt{Hz}$.

The setting of the max VGA gain can be changed to adapt the amplification of signals generated by higher energy impact to avoid saturation, for example a Vs = 200 mV. $Av_{TOT(dB)}$ can be now recalculated by (2) for this case:

$$Av_{TOT(dB)} = 3V/0.2V = 15 \text{ V/V} \tag{5}$$

According to (3) the Vn_in (ADC) increases to the new value:

$$Vn\_in \text{ (ADC)} = Vn(ADC) / Av_{TOT(dB)} = 30 \text{ nV} /\sqrt{Hz} \ / 15 = 2 \text{ nV} /\sqrt{Hz} \tag{6}$$

The new operating condition shows a decreased SNR performance being the ADC input noise exceeding the LNA noise. Assuming the worst case of the latter example for a bandwidth of B = 1 MHz, the equivalent input noise voltage is:

$$Vn\_in\_equivalent \text{ (B=1 MHz)} = Vn\_in \text{ (ADC)} \times B = \ 2 \text{ nV} /\sqrt{Hz} \times \sqrt{1MHz} = 2 \text{ mV} \tag{7}$$

This value needs to be compared with the lower amplitude of the Lamb wave mode signal that can be received for a given sensor sensitivity, especially if a signal processing scheme is based on a threshold method. Often low impact velocity impacts generate fast $S_0$ mode signals in order of tens of microvolts and in that case the AAF must be designed to the minimum bandwidth requires and the voltage gain set to maximum available in the chain.

This simple example is useful to demonstrate one of the trade-offs for the design of the AFE when the input signal has large amplitude variations. A good example of this situation is the signal conditioning of an impact signal described in Section 1.2, where the generated $S_0$ leads the slower $A_0$ and the amplitude ratio between the two signals can be 10-fold factor.

These problems (SNR, gain setting, dynamic) are partially overcome today by using COTS integrated circuit for AFE, but their characteristics are often optimized for the NDT and medical ultrasound sensors, while for the SHM the input voltage levels and bandwidth differ from those fields. Moreover, the integrated devices that include ADC have steady state power consumption compatible with power supply unit for electronics in a base station (see Figure 8) but such power consumptions are rather demanding when the electronic front end is close to the sensor, as for the solution of a battery operated node for a sensor network. Yun in his master thesis (available at https://vtechworks.lib.vt.edu/handle/10919/42507) have proposed an electronic solution for impact detection with nodes implementing EMI method where the impact signal triggers a low power comparator that switch on the power supply of the rest of the electronics for acquiring the signal over a defined amount of time. This type of solution alleviates the problem of power supply for continuous monitoring. Thomas et al [94] demonstrated that a coverage with rings of AE sensors installed on composite tube can produce high quality images of damages by an EMI tomographic method.

Another electronic design issue is the pick-up of environmental noise when broadband sensors are adopted. The extrinsic electromagnetic noise picked up by the wiring of the sensor to the AFE, is an additional source of SNR deterioration unless bulk coaxial cables are used. A quite robust solution that mitigate the common mode noise is the differential connection of the sensors, but this implies the design of special differential amplifiers with high CMRR at the operating frequency as reported by Boukabache et al [95] and Capineri et al [96].

**3.2 Real time electronics for impact monitoring**

In this section we review the developments on real time electronics for monitoring multiple impacts with multichannel inputs capability that is a mandatory feature for implementing large sensor network experiments and installation.

From the research point of view is also very important to test the whole SHM with multiple impacts to gather many signals in real time as shown by Ren et al [97]. This approach allows with laboratory experiments to simulate repetitive impacts at different energy levels and periods to test and optimize the sensor layout and electronic signal conditioning parameters. The multiple impact experiments can be done in laboratory with programmable mechanical impactors as reported in [33] and [56]. This solution is very useful for avoiding time consuming experiments based on pencil-lead break (PLB) tool for the collection of large signal data bases to test advanced algorithms (see Ebrahimkhanlou et al [93]). Impact detection and positioning is obtained with several sensors (at least three) deployed on the structure with a strategy for uniform area coverage and detection sensitivity.

For these reasons, several recent works have proposed real-time electronic platform with multichannel capabilities to overcome the main limitation offered by the common solution of using a general-purpose digital oscilloscope. A real-time electronic platform design for passive and active mode functionalities was published by the authors Capineri et al [98], while Yuan et al [99] designed a low-cost signal acquisition system based on sensors tags with local preprocessing capability.

In early works published by Ziola [42], the evolution from narrow to broad bandwidth sensors and analog front-end systems was proposed to locate the acoustic source more accurately as the spatial resolution is improved by using higher frequency UGM. Impact velocity and energy variability generates different modes and for the calibration tests are often recommended low energy impacts carried out with the PLB as acoustic source, as reported by Wilcox et al [48]. The advantages of retrieving information from broadband signals are also discussed by Gao et al [100].

### 3.3 MEMS sensors, CMUT, PMUT and integration with electronics

The progresses of Micromachined Electrical Mechanical Systems (MEMS) in the last two decades have opened the research for a new class of sensors for AE and SHM. MEMS technology have received a great success to integrate sensors with electronics, especially for achieving mass production at low cost with integrated circuit technologies; tri-axial capacitive MEMS accelerometers is probably the first example of such integration process started in the 80's and now has achieved important results in multisensory nodes (MOTES) as reported by Glaser et al [101]. In this section the focus is about deterministic sensors for SHM and AE based on UGW both for passive and active mode as introduced in Section 1. The interest of deterministic sensor capable to directly produce flaw detection and flaw growth attracted the interest to find alternative to PZT, AlN, ZnO piezoelectric/piezoresistive UGW devices. Actuation and sensing UGWs by capacitive MEMS is derived by the first study of Haller et al [102] at Ginzton Laboratory, Stanford University, based on the electrostatic actuation of a thin silicon membrane. At first capacitive MEMS technology was meant for improving airborne ultrasonic transducers, but

it revealed immediately the potential application for generating Lamb waves in solid materials (see Yaralioglu et al [103]); after two decades the recent advancement of capacitive MEMS sensors in design, fabrication and integration with electronics can be found in the review paper of B.T. Khury Yakub [104]. Since then, the effort for designing small scale factor CMUTs for SHM and AE has been great and different design and fabrication methods have been proposed by PhD dissertation of Bradley [105] and recently by Butaud et al [106]. CMUTs are generally designed as resonant devices and the resonant frequency depends on the bias voltage. The front-end electronics for CMUT is generally different from that one required for low impedance piezoelectric devices; the essentially capacitive behavior of the sensor impedance requires a custom design of the LNA (see signal chain in Figure 9). In this regard for testing commercially available CMUTs in laboratory setups, charge amplifiers as CA7/C by Cooknell Electronics Ltd have been used by Bradley [105] and Butaud et al [106], while the opportunity to on chip integrated multichannel AFE for CMUTs was reported by Savoia et al [107]; more recently the approach of monolithic integration of a CMUT array with ASIC based on flip-chip bonding has been presented by B.T. Khury-Yakub [104]. For the detection of Lamb waves, CMUTs need still to be improved in terms of sensitivity and signal to noise ratio respect to conventional piezoelectric sensors as reported by Boubenia et al [108]. MEMS technologies were also applied for designing and fabricating piezoelectric devices. Generally speaking, a piezoelectric MEMS sensor for SHM is based on a resonating silicon microstructure and a thin piezoelectric material layer and assembled in a ceramic package. The main advantage is to retain the high electromechanical coupling coefficient of piezoelectric materials with the advantage of a significant reduction in size and weight. The

latter are promising features for an ease installation on structures and possible embedment. An alternative technology for sensor systems size reduction are Piezo-MEMS. There are two recent works published by Ozevin et al [109] reviewing the advancements of piezo-MEMS operating in the 40-200kHz frequency range. In the reference [110] are also reported MEMS based on both piezoresistive materials that need to be supplied by constant current sources and they need also to be temperature compensated; the same review work describes also another type of capacitive sensors for AE that differs from CMUT as it is based on the change of capacitance in response to a dynamic stimulus that varies the distance of the electrode plates. This principle well known in capacitive MEMS accelerometers is demonstrated for in plane wave sensing through a differential capacitance sensor for AE applications [111]. That review paper also addresses to the main difference between broadband and narrowband devices: while the latter have high sensitivity at the designed resonant frequency with high Q factor, the broadband are more versatile devices, but the sensitivity is not yet comparable with analog bulk piezoelectric sensors. The increase of active area of the piezo MEMS increases the sensitivity but the footprint goes closer to those of conventional piezoelectric sensors. However, for some applications where high energy impacts generates large amplitude stress waves in the structure, the lower sensitivity of MEMS sensors can be acceptable. Despite these advantages of miniaturization and integration with AFE circuits, these devices lack of experimentation in harsh environment or at least in simulated operative conditions for aerospace, automotive and civil engineering applications. A recent review paper that discusses also the additional problems when the sensors are attached permanently to a structure has been published by Guemes et al [112]:

the reliability of the entire SHM system needs to be studied with more focus in order to demonstrate the sensor and electronics technology for real life applications. Finally another MEMS technology investigated for AE sensor is the piezoelectric micromachined ultrasonic transducer (PMUT), first introduced in the 90's for ultrasonic applications in the 100kHz- 15 MHz range by Percin et al [113], Muralt et al [114] and Bernstein et al [115]. The main concept for the P-MUT device was the design of a sensor based on laminated structures vibrating in the bending mode by combining rigidity and strain of beam and plate microstructures. This technology has been also applied recently for AE sensor and Feng et al [116] developed a PZT micromachined cantilever-based sensor. The comparison of the new PMUT device with a commercial sensor seems promising besides the characteristics (gain, bandwidth, filtering) of two adopted AFEs should be compared.

**4. Hardware developments of wired and wireless sensor networks (WSNs) for SHM and validation tests.**
From the previous sections it turns out that in the recent years the combination of several progresses in sensors and mixed signals low power electronics have introduced a new paradigm for the SHM systems that is the network of sensors nodes, as reported by Farrar et al **[117]**. A conceptual description of the migration from single distributed sensors on a structure to the sensor network is shown in Figure 10, where for example the authors represented a sensor network for monitoring a COPV system. In the same picture are shown the main electronic blocks needed to realize a sensor node with active and passive mode operation. Both the transducer driver (for broadband or narrow band ultrasonic transducers) and the signal conditioning are controlled by a mixed signal System on Chip

(SoC). The connections between nodes and the central unit (see architecture in Figure 8) can be implemented with wired solutions where the power lines for the nodes can sustain a sufficient data rate by using power line communication (PLC) protocols and related chipset. Simplified connection schemes and low power digital electronic front end has been recently proposed and validated on an aircraft wing by Qiu et al **[67]**.
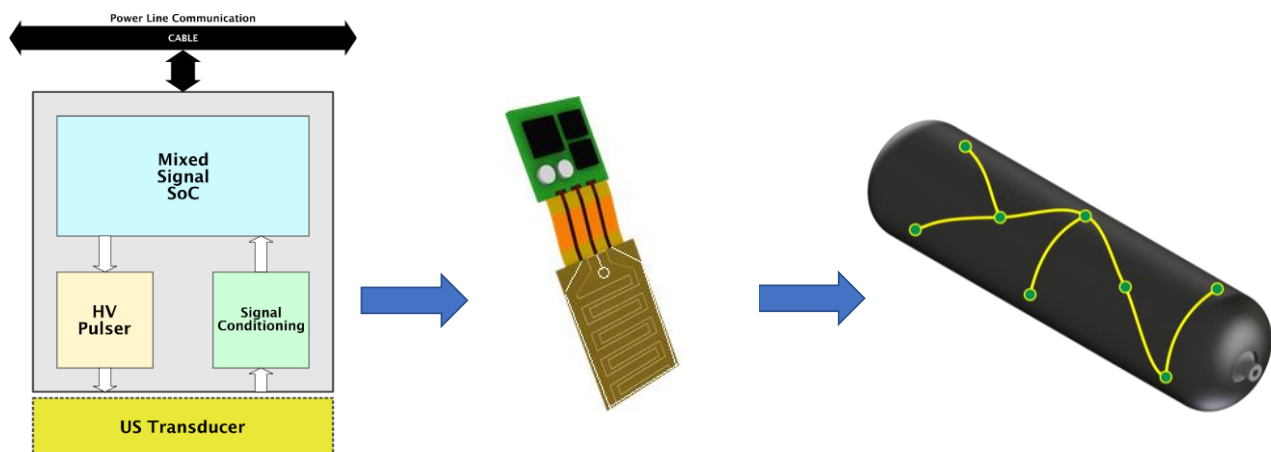
Figure 10 A wired sensor network based on node design. In the example each node uses a PVDF multifunctional IDT: (a) node electronic block scheme; (b) node rendering; (c) rendering of a possible application to a COPV equipped with a wired sensor network.

One of the first implementation of this paradigm was published by Schubert et al **[90]** with the Match-X project of the Fraunhofer Institute. The node design and electronic integration with a stack on miniaturized PCB with SMD components with embedded PZT transducers mounted on a glass-fiber-reinforced-polymer (GFRP) plate. The paper addressed also to the requirement of power supply overvoltage protection and detection of failure events that is one important consideration for self-diagnostic of nodes. Lehmann et al **[36]** presented in the same year the results of validation of the embedded PZT MFC transducers in an aircraft wing. Local processing of the acoustic signatures was demonstrated by the integration of the AFE in the node architecture: the ADC, and algorithms for data reduction, and digital

communication thanks to the use of a DSP. Besides the adopted solution for data transfer

was based on a two wires industrial CAN bus, the authors introduced an expandable feature

to open the wireless connection with a Bluetooth module, that recently have evolved in

Wireless Sensor Networks (WSN). The main electronic blocks of a sensor node for a WSN

are shown in Figure 11.
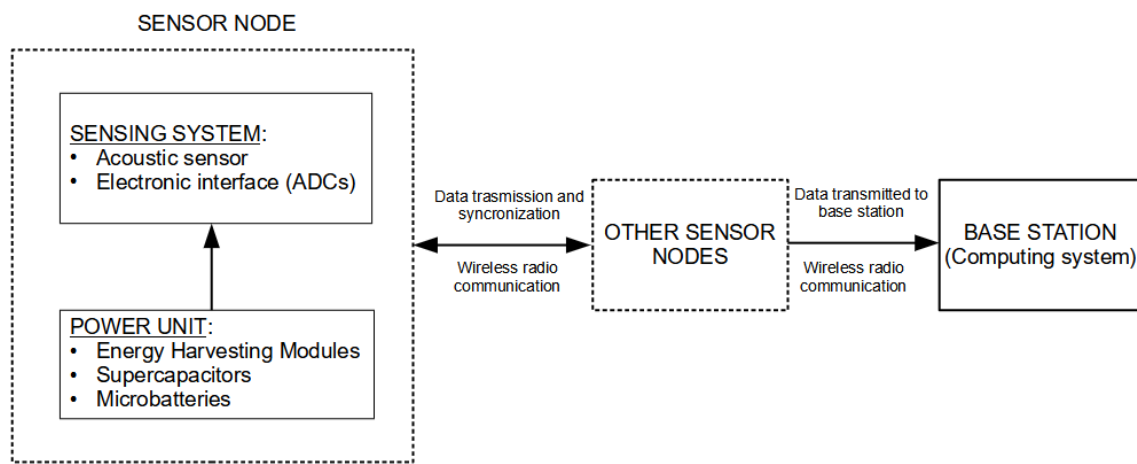
Figure 11 A block diagram of a wireless sensor network for SHM connected to a base station.

**4.1 Nodes and modules with low power electronics solutions with energy harvesting**

The main evolution for continuous impacts monitoring is the concept of autonomous nodes.

In the case of an SHM system we can observe that environmental operating conditions as

those described in Figure 1, are represented by different type of energy exchanges with the

structure. This interaction from the point of view of the impact event capture is seen as a

disturbance or noise but from the point of view of local energy accumulation can represent

an opportunity.

A preliminary work for this evolution was published by Champaigne et al **[118]** describing

a SHM system with wireless connection to interface up to four PZT sensors but with the

AFE capable to match different type of sensors. In that paper low power electronics available at that time was adopted to be compatible with charge capacity of a dual AA-cell battery pack to reach a operational time up to 10 total hours. A consideration must be made about the careful choice done for digital electronics such as the ADC, FPGA and digital communication, that are typically power angry devices. A recent paper that can solve the power demands for continuous monitoring is proposed by Fu et al **[119]** and the solutions consists of keeping in a sleep mode a section of the digital electronic processing until a detected event switches on the power supply of the  data acquisition and processing blocks; a similar approach with a compact electronic design for a wireless smart sensor node was published by Overly et al **[120]**. In the latter work were used low power chips and self-diagnostic for the detection of PZT elements debonding from an aircraft wing. Another important design issue that is tackled in the paper, is the temporal synchronization of data from an impact event detected by the WSN; this topic will be expanded in the section 4.2. The design of a WSN with low power budget obtained by the sleep mode operability is presented by Giannì et al **[121]**; in particular the authors analyze the design issues regarding the AFE+ADC noise characteristics and their influence on the errors achievable for impact positioning with a triangulation method.

Ferin et al **[91]** presented a new hardware development of a highly versatile of energy autonomous acoustic sensor node that is an element of an intelligent wireless network, capable to host and run various ultrasonic inspection algorithms. The energy harvester was the conversion from mechanical vibrations into electrical energy stored in a supercapacitor with a high charge capacity/volume ratio. In this paper the hardware specifications for an

automated and remote aircraft ultrasound inspection were considered as a started point for a product-oriented research. Taking advantages of low power electronics with energy harvesting solutions, the design of a MEMS piezoelectric power module converter with power density of $6mW/cm^3/g^2$ and an output power around $120\mu W$ was presented. To cover the full power supply demands of a sensor node, multiple MEMS power module can be connected at the expense of an increased volume occupation. The piezoelectric energy harvester system was capable to charge a thin film battery (EFL700A39 from STM - $700\mu A/h$ 3.9V). The topic of energy harvesting is strictly related to design autonomous sensor node and several review papers for the interested reader as Mateu et **[122]**, Sodano et al **[123]**, Trigona et al **[124]** and an example of a small scale factor energy harvester device is reported in Figure 12. Authors presented in **[124]** a prototype system for delivering energy to SHM sensor nodes by microwave wireless energy transmission in the 10 GHz X-band. The energy harvesting for low power WSN with special emphasis to SMH application has been reviewed also by Park et al **[125]**. Finally, the outcomes of a recent project dedicated on the energy harvesting methods for SHM systems installed on airplanes have been published by Zelenika et al. **[126]**.
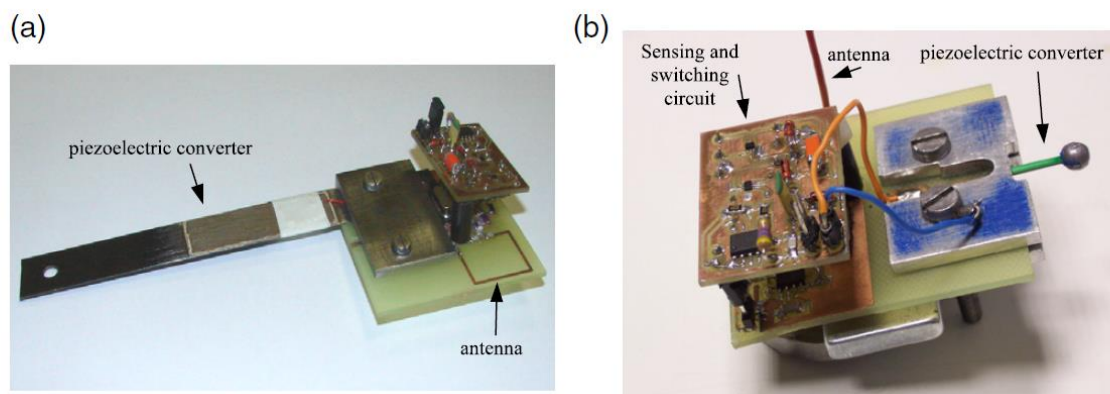
Figure 12 . The realized prototype of the autonomous sensor module with a thick-film piezoelectric converter
(a) and with a commercial piezoelectric converter (b) (adapted from [127] with authors permission).

It is worth to mention also industrial projects covering the WSN approach for aircraft SHM

as proposed by METIS Design company (www.metisdesign.com) and the European Project

"FLite Instrumentation TEst Wireless Sensor",

(http://cordis.europa.eu/project/rcn/108855_en.html). Another kind of sensor network

formed by modules connected by fiber optics to obtain large immunity from environmental

electromagnetic noise, was presented by Smithard et al in **[128]**. The Acousto Ultrasonic

Structural health monitoring Array Module (AUSAM) project relies on autonomous

electronic modules designed with off-the shelf electronic components that interface up to 62

PWAS. These modules can operate in active and passive mode and are equipped also with

an EMI module, the latter is usefully adopted for checking the reliability of the PWASs. A

futuristic vision of the AUSAM module is the transportation and installation on the

structure by a drone, with envisaged advantages on maintenance service performance and

costs. A similar idea of using drones for EMI technique has been recently reported by Na et

al **[70]**. The interest of sensor networks for SHM in transportation and civil engineering

infrastructures also requires a different approach for system performance evaluation; Ju et

al **[129]** proposed a simulation of a sensor network for continuous monitoring of railroads

where fast transportation systems are in service. Sundaram et al **[130]** reviewed the

advantages of WSN for SHM of large civil engineering structured and pointed out the

problem of connection reliability, obstructions to radio links and finally the energy

harvesting.

Ren et al **[131]** presented a strategy for radio communication of autonomous nodes for impact monitoring of large structure and a preliminary validation on a laboratory mockup of an air wing is presented. The original solution is the adoption of a multi-channel radio communication on different frequency channels to improve the data transmission capability and the reliability of the WSN. Embedded computational resources in sensors nodes for vibration monitoring has been designed and tested on a laboratory mock up by Testoni et al **[132]**; this work shows a design with volume/weigh constraints and power consumption of a node requirements for implementing a wired sensor network based with PCL.

Summarizing the outcomes of the works reviewed in this section we can say that are now available technologies for embedded signal processing, signal transmission with low power that can also be integrated with energy harvester devices that are mainly demonstrated in laboratory experiments, but some real-life cases started to be present in the literature. In the next section we will made a discussion of the issues for a wide spreading of smart nodes for SHM networks.

### 4.2 Toward SHM sensor networks with smart nodes

From the previous paragraph it is clear the interest to move SHM system toward sensor networks and in the following we draw some general comments and challenges for addressing the next steps for new developments. In this section we discuss the advancements of smart nodes in the perspective of an impact sensing SHM network.

One of the topics that is now under the attention of the research is the evaluation of data transfer requirements for a node. The reduction of data rate will bring the characteristic to

change a node to a "smart-node" as some local processing is needed. The data rate reduction is achievable by compressive sensing techniques as investigated by Mascarenas in [133]. The recent research on this subject demonstrated also benefits for the autonomous detection and localization of an AE source, as we will explain later in section 5.

The presence of smart sensor nodes, and a relatively dense interconnection network, can provide some degree of redundancy to the SHM system, where failing sensor nodes will not compromise the operation of the overall system. Of course, the thickening of the interconnection network goes against the minimum-encumbrance policy, that is one of the original goals of the sensor network architecture, but it is a trade-off that should be considered, nonetheless. From the point of view of harnessing, PLC represent a way to achieve the minimum amount of cabling required to route the sensor network, albeit at the cost of reduced bandwidth. A problem that is deeply ingrained in sensor networks that need to cooperate in the ways described above is how to achieve and maintain inter-node synchronization. Although the topic has not been addressed so far, the problem of synchronization in measurement and control networks is well known and will be approached starting from the provisions of the Precise Time Protocol (PTP) IEEE 1588 standard that can reach a synchronization accuracy of 0.1 µs wired network connected on ethernet. Such performance is compatible with SHM sensor network design being the UGW signals with frequency content below 1MHz and TOF in the order of 10 µs - 100 µs. This analysis derives from the main requirement that each sensor nodes need to be synchronized up to a fraction of the DToA to produce data useful for accurate impact positions. The

synchronization problem is even more complex for WSNs and the next section will go in some detail of the proposed solutions.

### 4.3 WSN and IoT for SHM

In the last few years, the concept of WSN for SHM has moved on to the IoT for SHM. The main advantage of introducing the communication of a WSN for SHM over internet comes from the possibility to uniquely identify data packet generated a sensor node, large bandwidth for data transmission and time correlation thanks to the accurate synchronization of nodes. Moreover, the large storage capacity of the cloud allows to implement further the data interpretation by using AI and deep learning for Big Data; some examples of the latter novel development will be reported in the next section.

Tokognon et al [134] have well reviewed the challenges for the design SHM using IoT technologies to achieve intelligent and reliable WSN for monitoring structures. The authors identify three main blocks to be integrated for this aim:

- Sensing and data Acquisition Subsystem.

- Data Management Subsystem: preprocessing methods used to organize raw data acquired from sensors and remove noise before processing; novelty detection, classification, and regression approaches. Among them, novelty detection based on artificial neural networks.

- Data Access and Retrieval Subsystem.

The requirement of low power communication technology based on IPv6 assignment of a node is analyzed for battery operated sensors. ZigBee Alliance working has accelerated the expansion of the sensor network and building automation market. From the PHY and MAC layers defined in the IEEE 802.15.4 standards Zigbee considers networking and services layer, through the full application layer. ZigBee PRO was developed specifically for device-to-device communication in IoT context.

Unfortunately, WSN based on IEEE 802.15.4/ZigBee do not currently support IP, due mainly for the small length of packets used in IEEE 802.15.4. Therefore, most of the solutions proposed consist of using IP proxy or gateways. A network configuration strategy for WSN configuration with sink nodes at the edge of the network, also called border routers, with IP protocol connection over Internet is presented in the paper by Tokognon et al [134]. From the sink nodes data can be transferred with JavaScript object notation (JSON) to a Web server where a large storage capacity is commonly available.

Moreover, the Internet Engineering Task Force (IETF) defined the 6LoWPAN standard (RFC 4944) to allow the use of IPv6 packets over IEEE802.15.4 networks. It compressed IP headers to resolve packets size issue and fragmentation mechanism to transmit IP packets over IEEE802.15.4 networks. IETF also started a working group to evaluate appropriate routing protocols for low-power (RPL) and lossy networks.

As stated in the previous section the node synchronization is another challenge for a distributed IoT. Scuro et al [135] published a work devoted to this problem and a solution was proposed with each is equipped with a clock, and typically they exchange

synchronization messages to evaluate the frequency and the offset of their clock with respect to one taken as reference (master) or with respect to its neighbor sensor node. This solution implies an additional overhead, since extra messages and re-synchronization periods are required.

In the same structure, local area networks with routers that give priority to the transmission of the synchronization messages, or that compensate for the transmission delay, can be deployed. In these cases, synchronization accuracy in the order of microseconds is still achievable. In fact, for the SHM system the typical accuracy needed between the node is in the range [0.6, 9.0]µs. Muttillo et al [136] presented a solution for structural monitoring with digital accelerometers ADXL355 with high resolution connected to hardware for IoT connection. To preserve such performance a high synchronization between the sensors was implemented.

Finally, example of prototype architectures for WSN nodes connected on ethernet based on Raspberry Pi have been presented by Abdelgawad et al [137] and Mahmud et al [138]. Besides the power consumption of these design was a neglected factor, the two systems were successfully demonstrated for SHM in laboratory.

### 5. Artificial Intelligence and Machine Learning.

The previous sections pointed out how embedded sensors with low power electronics in a sensor node enable SHM monitoring networks on IOT for large and complex structures. This new paradigm also brings the large data collection and data interpretation challenges. In this section are discussed the recent approaches based on Big Data (BD) and Artificial

Intelligence (AI) and then we complete the review of all SHM system components shown in Figure 1.

One of the early papers on this subject was published by Farrar and Worden [5]. The authors pioneered this subject with the introduction of the machine learning/statistical pattern recognition paradigm for SHM. Since then, in the last decades remarkable developments have been done.

Worden et al [139] analyzed the non-stationary properties of the Lamb waves used in SHM and how the machine learning approach can solve the operator-based data interpretation that results difficult and time consuming.

As said above, BD can potentially enable the automatic classification of defects, but the reduction of input data remains a goal to simplify the design of the processing task, as proposed by Bao et al [140]. The application of compressive sampling of sensors signals is a useful strategy and in particular for Lamb waves, it is worth to mention the work of Bao et al [140] where a CNN was trained with experimental data.

Yuhan et al [141] observed that in many practical situations the data set are limited to a small period of monitoring time and generated by a specific part of a complex structure and this limits the performance achievable with ML. That work analyzed a possible solution based on physics-informed learning, that integrate information derived from physics-based model into the learning process. Examples of physics-informed Deep Learning (DL) approach applied for low-velocity impact diagnosis is reported. For this aim a pipeline consisting of a unified CNN-RNN network architecture for spatial-temporal analysis of the

impact generated wavefield was developed. The knowledge type of physical principles was based on classic Huygens principle, time-reversal methods Fink et al [28] and simulated data based on dispersive propagation model of generated waves from impacts. This knowledge was introduced in the CNN network of the data processing pipeline and helps to define a vector feature for the learning and classification. The autonomous detection of defects in plate-like metal panels was investigated by Hesser et al [142] with a ANN trained by signals acquired by four commercial sensors (PIC255 from PI Ceramic) with 1 MHz sampling rate and 16 bit resolution ADC. The experimental data set was generated by free falling ball impact at low velocity (about 1 m/s) that are converted in large amplitude, low phase velocity $A_0$ mode Lamb waves. By this approach is demonstrated that the achievable spatial accuracy is in the order of the wavelength corresponding to the main $A_0$ received mode with frequency content well below 100 kHz. Another paper following the work of Hesser is published by Mariani et al [143] where the autonomous defects classification is explored with a CNN approach that overcome the limitations of extensive baseline data archives.

Sun et al [144] have reviewed the framework for the development of damage detection in civil engineering infrastructures (bridges) where big data can be acquired in real time and artificial intelligence strategies need to be adopted.

An interesting approach based on data driven models, is the application of DL with ANN to directly input raw data from a limited number of sensors for impact localization and characterization is published by Ebrahimkhanlou et al [93]. In that paper a deep network is

trained on simulated and experimental data sets with signals received by a very small number of sensors (from 1 to 4) covering the area of a test aluminum panel equal to 500mm x 500 mm. The single sensor solution is certainly attractive from the point of view of cabling and costs but for the system reliability a certain degree of redundancy is necessary by increasing the number of sensors which also improves the accuracy of impact area estimate and impact characterization.

Finally, we observe that the DL approach is capable to exploit information from signals acquired over a long-time interval, where multimodal dispersion and reverberations (multipath) effects are present.

## Conclusions

The paper reviews the recent developments of sensors and integrated SHM systems for impact detection focusing to novel techniques introduced in the last decade. The reader can find the new technologies that can be combined for the design of advanced SHM systems for impact monitoring that benefit from the recent advancements of UGW modelling, sensors materials for MEMS solutions and interface electronics, signal processing algorithms for real time applications, sensors nodes for WSN and IOT and the data processing with AI and Big Data.

In the first part of the paper are discussed the characteristics of UGW modes generated by impacts with the differentiation of low and high velocity impacts and their attenuation. The understanding of this physical background is relevant to indicate the different

characteristics (amplitude, velocity dispersion) of the signals that will be treated by the instrumentation. Then are reported with numerical examples the different characteristics of broadband patch-type piezoelectric sensors and the comparison with IDTs employed for Lamb wave mode selection. The introduction of novel piezoelectric (Carbon Nano Tubes, Microfiber Composites) materials for MEMS sensors for detection of impact signals is more recent but promising results have been reported; an outlook for CMUT and PMUT devices is also considered for integration of the electronics. The analysis of the impact monitoring systems concludes with the design issues for the front-end electronics that need to match with sensors characteristics and different type of impact signals. Environmental factors like temperature range, strain of structure, vibrations, have been also discussed because all these factors influence the choice of sensor; for the compensation of the environmental factors, the trend of the research is the design of multiple sensors nodes with mutifunctional capabilities, and some examples are reported. Comments on laboratory set-ups for testing integrated SHM systems for impact monitoring with active mode operability for damage assessment are reported to understand the gap respect to the complexity of real-life installations; for the latter, the analysis of the solution adopted and available in the literature is mainly addressed for aircraft and wind turbines in composite materials. For the design and installation of a sensor's layout is also important to establish the number of transducers and their connections to a base unit: new piezoelectric materials for the realization of a "smart skin" with stretchable/flexible sensors is discussed in detail. The increasing number of works on this subject in the literature indicates that is achievable a trade-off between number of sensors installed and the coverage of the full area under test.

For the data acquisition and processing of an always increasing number of sensors installed into the material under inspection, are reviewed the published integrated or embedded electronic systems.

In the second part of the review are addressed the combination of the several progresses in sensors technology with mixed signals low power electronics; such progresses have introduced a new paradigm for the SHM systems that is the network of sensors nodes and the main evolution for continuous impacts monitoring is the concept of "autonomous smart-nodes". A smart sensor usually has some essential features: on-board microprocessor; sensing capability; wireless communication; locally powered and low cost.

In the future autonomous sensor nodes will also exploit MEMS devices for energy harvesting and the most recent advancements in this field are reported.

State-of-the art for wireless communication involve the adoption of a multi-channel radio communication on different frequency channels to improve the data transmission capability and the reliability of the WSN. The main advantage of introducing the communication of a WSN for SHM over internet, comes from the possibility to uniquely identify data packet generated a sensor node, exploit the large bandwidth for data transmission and time correlation thanks to the accurate synchronization of nodes. The latency in the communication between WSN nodes has an impact on the error of the differential time of arrival, that is one of the basic information for impact positioning. Algorithms that can be embedded in a digital processor (microcontroller, FPGA, DSP) for features extraction useful for impact positioning algorithms are reported.

In the final part of the review are considered the most advanced integrated SHM systems: embedded sensors with low power electronics in a sensor node enable SHM monitoring networks on IOT for large and complex structures. This new paradigm also brings the large data collection and data interpretation challenges based on Big Data (BD) and Artificial Intelligence (AI). The results of this emerging research topic show that they can help to solve the signal interpretation of large sensors nodes installed on complex composite material structures, and the detection and positioning of an impact is obtainable with errors comparable to deterministic algorithms.

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**Appendix A**

Acronym

AAF   Anti Aliasing Filter

ADC   Analog to Digital Converter

AFC    Active Fiber Composite

AFE   Analog Front-End

AI      Artificial Intelligence

AIC    Akaike Information Criterion

AlN    Aluminum Nitride

ANN  Artificial Neural Network

ASCS  Aircraft Smart Composite Skin

ASIC   Application Specific Integrated Circuit

BD      Big Data

BSS     Bioinspired Stretchable Sensors

CAN   Controller Area Network

CMUT        Capacitive Micromachined Ultrasonic Transducers

CNT   Carbon Nanotubes

COPV Composite Overwrapped Pressure Vessel

CWT   Continuous Wavelet Transform

DSP    Digital Signal Processor

DTOA        Differential Time of Arrival

EMAT        Electro Magnetic Acoustic Transducer

EMI    Electro-Mechanical Impedance

FBG    Fiber Bragg Grating

FPC    Flexible printed circuit

FPGA Field Programmable Gate Array

FUT    Flexible Ultrasonic Transducers

GFRP  Glass Fiber Reinforced Polymer

IDT    Interdigital Transducer

INA    Instrumentation Amplifier

IoT    Internet of Things

ISHM  Integrated Structural Health Monitoring

LNA    Low Noise Amplifier

MEMS        Micro Electrical Mechanical System

MFC    Macro Fiber Composite

ML     Machine Learning

NDE    Non Destructive Evaluation

NDI    Non Destructive Inspection

NDT    Non Destructive Testing

NF     Noise Figure

PLC    Power Line Communication

PMUT        Piezoelectric Micromachined Ultrasonic Transducers

PTP    Precise Time Protocol

PVDF   Polyvinylidene fluoride

PVDF–TrFE   Polyvinyledenedifluoride–trifluoroethylene copolymer

PZT    Lead zirconate titanate

PWAS        Piezoelectric Wafer Active Sensors

ROI    region of interest

RPL    Routing protocols for low-power networks

RTD    Resistive Temperature Device

SH     Shear Horizontal

SHM    Structural Health Monitoring

SiC    Silicon Carbide

SL     SMART Layer®

SS     Smart-Skin

SLDV  Scanning Laser Doppler Vibrometer

SNR    Signal to Noise Ratio

SOC    System on Chip

STFT   Short Time Fourier Transform

TGC    Time Gain Compensation

TOF    Time of Flight

UGM   Ultrasonic Guided Mode

UGW   Ultrasonic Guided Wave

VGA    Variable Gain Amplifier

WSN   Wireless Sensor Network