Chapter 1

Smart and Sustainable Wireless Sensor Networks for Structural Health Monitoring

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Abstract

This chapter identifies the prevalent challenges in designing sensor networks for structural health monitoring applications and presents the recently evolving technologies in embedded computing, energy harvesting and wireless communications. In particular, continuous monitoring with spatially distributed passive acoustic sensors is highlighted. Introduction of smart wireless sensor nodes enables local processing and decision making capability. In addition, the combination of smart power management and energy harvesting techniques results in sustainable sensor operations, critical for broader adoption of structural health monitoring applications.

1.1 Introduction

Operational safety of infrastructures such as bridges, interstate highways and power grids, is a significant issue with immediate public safety ramifications, in addition to economic losses and road network disruption concerns. Currently, keeping roads and bridges in a safe operating condition is a major financial burden on state departments of transportation as well as many local agencies. State and local agencies have to rely on limited data (primarily from subjective ratings provided by inspectors) to prioritize structures for repair and retrofit. In many instances, such information is not conclusive and may result in an overlook on the part of authorities. There have been instances when bridges have received favorable ratings, while in reality there were hidden problems that were missed by visual inspections. A significant example of this scenario is the I-35W Minnesota Bridge that failed due to design anomalies in gusset plates [Holt and Hartmann, 2008]. There also have been cases of corrosion of pre-stressing tendons in box girder bridges leading to severe damage (e.g., Mid-Bay Bridge near Destin, Florida) [Hartt and Venugopalan, 2002] – conditions that often may be missed using visual inspections. It is evident that the current condition of roads and bridges imposes a critical national issue. The American Society of Civil Engineers (ASCE) in its 2009 report card of the infrastructure conditions gives a score of "D" and specifically lists bridges among critical infrastructure systems [ASCE 2009]. According to this report, five-year spending estimate for infrastructure needs reaches $2.2 trillion.

Wireless sensor networks have been proposed extensively over the past several years as a means of alleviating instrumentation costs associated with structural health monitoring of civil infrastructure. However, low data throughput, unacceptable packet yield rates, and limited system resources have generally plagued many deployments by limiting the number of sensors and their sampling rate. The sensor networks present challenges in three broad areas: energy consumption, network configuration and interaction with the physical world. Therefore, the development of sensor networks requires technologies from three different research areas: sensing, communication, and computing (including hardware, software, and algorithms). The next generation of the structural health monitoring sensors needs to be low-cost, low-power, self-healing, self-organized, and compact.

The key to achieving these objectives is seamless integration of sensor clusters, processing engines for on-site signal processing, operational control, and wireless mesh network communications. Fig. 1.1 shows the main components of a distributed sensor system. In this system, all hardware (sensors, network, processing core) and software (signal processing, operational control and power management) components are designed to be application specific, thereby eliminating the ad-hoc approach prevalent today for structural sensing and monitoring.

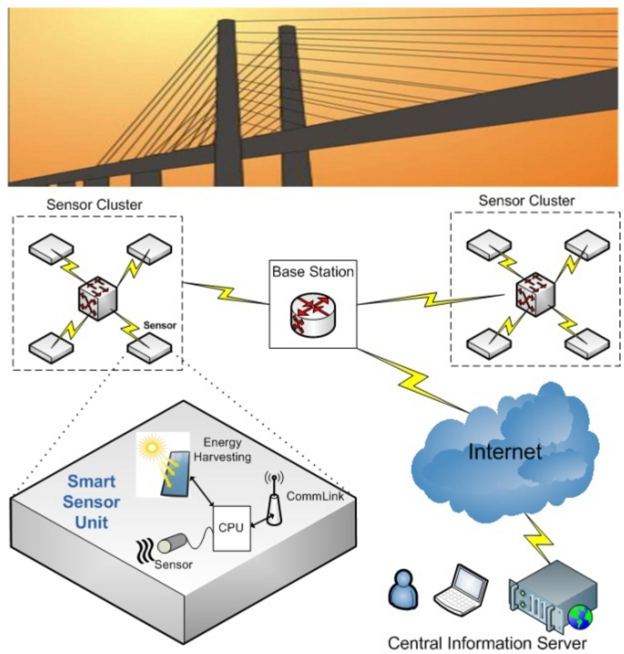

Fig. 1.1. Sensor networks for structural health monitoring

The organization of the chapter is as follows. Section 2 presents the continuous, passive sensor operations using acoustic emission. An advanced sensing and signal processing methodology is described for automatic defect monitoring related to generation and propagation of cracks using smart processing nodes. Section 3 highlights the need for improved network layer design for wireless health monitoring applications concerning the network lifetime and stability, reliability, self-formation, and distributed processing. Section 4 discusses the smart sensor system-on-chip (SoC) design based on reconfigurable hardware and shows the necessity of smart sensors for executing more advanced algorithms, reducing the frequency of RF transmissions, and achieving better power management. Section 5 describes the power consumption for key components and overall energy requirements in the smart wireless sensor network. A redundant energy harvesting and power management system is shown for achieving autonomous and sustainable structural health monitoring operations. Section 6 provides references for further information in this topic and Section 7 concludes the chapter.

1.2 Structural Health Monitoring using Smart Acoustic Emission Sensors

The current methods of structural monitoring for fatigue investigation in bridges have in most part relied on data gathered using strain gages installed at critical locations (e.g., [Mohammadi *et al*., 2004]). The data is then used to develop stress histories for use along with fatigue characteristics of critical components to (a) estimate the extent of damage and (b) predict the remaining life. Recent advances in sensor technologies and on-site data analysis have been instrumental in expediting the process and providing for a quick access to data (e.g., [Howell and Shenton, 2006]). Although there have been many attempts to incorporate fatigue analyses within a comprehensive bridge management system (e.g. [Messervey *et al.,* 2006]) or a global bridge health monitoring system (e.g., [Nassif *et al.,* 2006], [Sumitro and Hodge, 2006]), the underlying method still relies on using field data from sensors installed at critical locations. The most prevalent obstacles in preventing a widespread application of health monitoring in fatigue investigation of bridges have been (a) sensor installation being cumbersome and expensive (requiring mounting sensors at critical locations), (b) high cost associated with maintenance of the monitoring system and its need for a reliable power supply, (c) lack of sensor reliability, and (d) lack of a comprehensive network of sensors for compiling data on a multi component platform. These important challenges can be addressed with smart sensor technologies such as acoustic emission and intelligent pattern recognition methods executed at the sensor node level.

Acoustic Emission (AE) method is a highly effective technique in nondestructive evaluation of materials, in particular, for inspecting steel bridge superstructures [Kruger *et al.,* 2007], [Wilcox *et al.,* 2006]. AE is a phenomenon whereby transient elastic waves are generated by the rapid release of energy from localized sources such as cracks within a material under stress [Grosse and Ohtsu, 2008]. Fig. 1.2 shows the detection of AE signal from nucleation of a crack. For defect detection and classification applications, signal processing is necessary to extract the critical signal parameters such as arrival time, rise time, duration time, energy, frequency, peak amplitude, which corresponds to size, type and location of cracks [Ince *et al.,* 2009]. For structural health monitoring, multiple array of transducers can be mounted at several points on the structure, with the aim of detecting the presence, location, and intensity of acoustic signals generated by cracks and fractures (see Fig. 1.3). AE technique for structural health monitoring offers several advantages:

- AE provides passive and global monitoring of defects for nondestructive testing applications.
- AE signal parameters (arrival time, rise time, duration time, energy, frequency, peak amplitude) provide critical information about defects inside the material.
- With the recent advances in embedded SoC systems, on-going and unattended monitoring of structures using acoustic emission technique is feasible.
- Real-time monitoring of AE signal is highly practical, cost-effective and consumes minimal power using the proposed SoC hardware.
- AE sensors passively detect emissions from acoustic sources, unlike pulse-echo ultrasonic testing methods where ultrasonic waves are generated actively.
- AE signal reveals information about the defects, and the severity of the load and the strain impacting the structure.
- AE contains frequency signatures (ranging from kHz to MHz) that can be correlated to the characteristics of structural defects.

In order to achieve a comprehensive evaluation of source, location, size, severity, and type of defects; advanced time-frequency signal processing methods (such as wavelet transform [Oruklu and Saniie, 2004], split-spectrum processing [Oruklu and Saniie, 2009], Hilbert-

Huang transform [Oruklu *et al.,* 2009], chirplet signal decomposition [Lu *et al.,* 2006], and neural networks [Yoon *et al.*, 2007] can be integrated in smart AE sensing systems. These methods require significant computing power and often have been dismissed due to their complexity. Nevertheless, a smart SoC based sensor platform is capable of handling the computational demand of these techniques for improved defect detection. Therefore, AE sensor arrays can be used as the primary tool for on-going sensing operations in detecting microcracks and fatigue in steel structures.

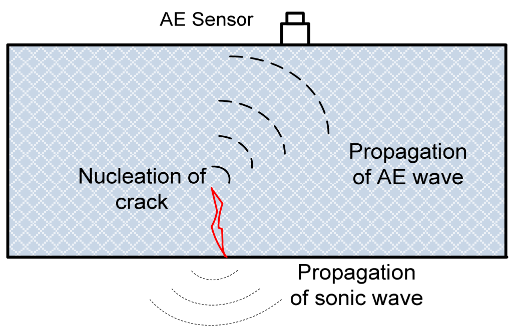

Fig. 1.2. Detection of AE signal from nucleation of crack

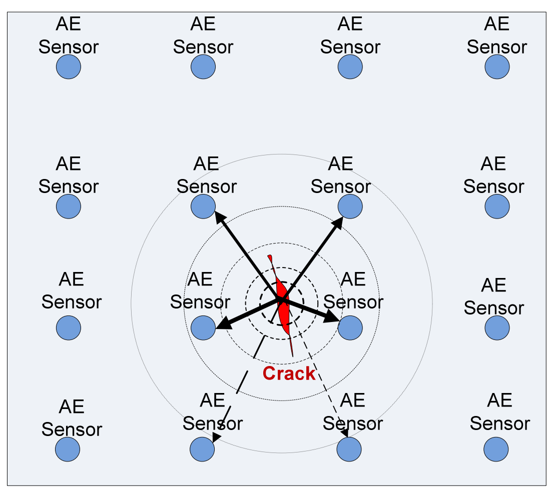

Fig. 1.3. Defect localization with AE sensor arrays

1.2.1 *AE sensing methodology*

The interpretation of the AE signals based on parameters such as duration, peak amplitude and energy, event number, ring-down count and time-of-arrival enables waveform analysis directly related with the geometrical shape, size and frequency of the acoustic discharge source. Hence, it provides continuous, automatic defect monitoring related to generation and propagation of cracks. Nevertheless, it is challenging to differentiate the signals associated with crack growth under stress from other noise sources. Another critical task is to identify and precisely locate the source of the structural deformities and cracks.

In order to address these challenges specifically, a multi-stage signal processing methodology can be applied for analyzing acoustic emission signals in structural health monitoring applications [Grosse *et al.*, 2006]. Fig. 1.4 shows the algorithm stages and the host system hardware used in distributed processing nodes.

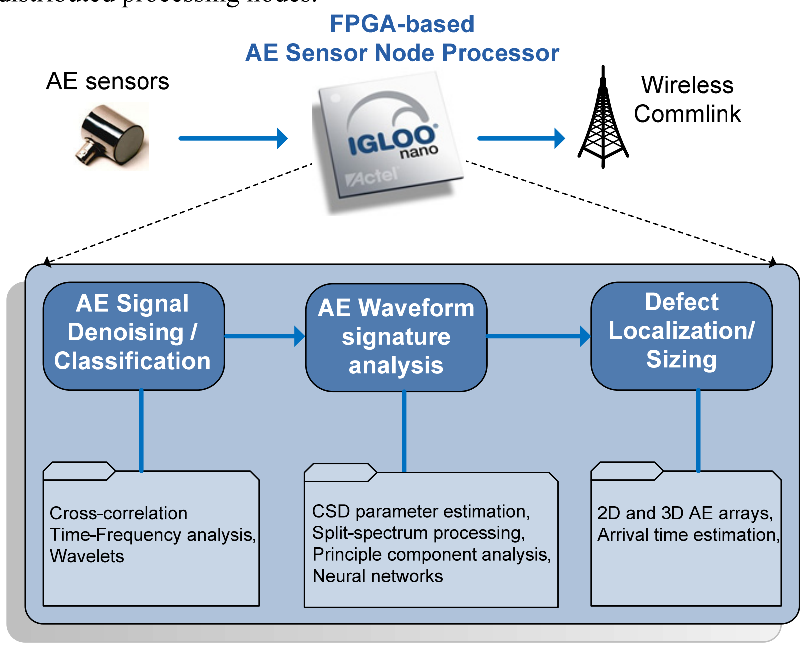

Fig. 1.4. Acoustic emission signal processing methodology for smart sensors

The algorithm stages are explained below:

AE signal denoising and classification: In addition to external sources and environmental effects, acoustic emission signals are also degraded by the experimentation setup, electronic and other sensor related noise. Smart sensor nodes make it possible to use advanced algorithms [Grosse and Reinhardt, 2002] for real-time denoising and signal classification of the AE signal.

AE waveform signature analysis: After signal denoising, the next step for analyzing any specimen under test is to isolate the acoustic emission signal induced by structural deformation from environmental interfering signals. This could be a very challenging task due to different operational environments such as railroad bridges where vibration during train crossings could be overpowering other signal sources. Before any analysis can be done, acoustic emission signature need to be identified from the incoming signal. The implementation of this signature analysis (i.e., pattern recognition task) [Ziola and Gorman, 1991] requires significant computation power due to correlation operations and necessary storage of signatures. Smart processing nodes based on FPGAs can handle these computations unlike most Mote based designs that utilize simple microcontrollers.

Defect localization and sizing: A major advantage of using distributed AE sensors (transducers) is the capability to find and pinpoint the exact location of the anomaly within the structure [Ince *et al.,* 2009], [Gross *et al.,* 1993]. Furthermore, the size and the geometrical shape of the defect can be recognized. For enhanced defect localization and sizing, multiple AE sensors can be used in a planar area requiring synchronization and time-of-arrival signal analysis among sensors. This necessitates communication among the sensor nodes and situational awareness (i.e., distance/location of neighboring AE sensors, network topology). Using positional data from AE sensors significantly increases the accuracy and performance of defect detection and characterization [Grosse and Ohtsu, 2008]. With the reconfigurable hardware coupled to each AE sensor array, smart arbitration and estimation of AE events can be implemented.

1.3 Wireless Sensor Networks for Structural Monitoring

Recently, wireless embedded sensor networks have emerged that can be characterized by local processing capabilities that minimize the amount of data transmitted in a single- or multi-hop strategy to extend the lifetime and robustness of the network. The multi-hop Wisden system [Xu *et al.,* 2004], which uses the small mica motes developed at the University of California at Berkeley [Horton *et al.,* 2002], provides an example. In this system, by avoiding the transmission of lengthy time histories, battery life of the wireless nodes can be extended, while the issues of strict time synchronization and loss intolerance are marginalized. The BriMon system [Chebrolu *et al.,* 2008] provides an easy to deploy, long term and low maintenance system using battery operated wireless sensor motes as an alternative for communication and data logging needs. While such developments in wireless sensor networks have demonstrated their potential to provide continuous structural response data to quantitatively assess structural health, many important issues including network lifetime and stability, reliability, time-synchronization, distributed processing and overall effectiveness when using low-cost sensors must be realistically addressed.

Due to the specific requirements of the structural health monitoring systems, many additional challenges need to be solved at the network level itself, apart from the coordination needed with the application layer. Specific problems include:

- Self-formation: The network topology should be self-adjustable, i.e. addition of new sensor devices should be handled automatically in the network without manual intervention. Similarly, the sensor devices may drop out of the network if enough energy is not harvested. In this case, the rest of the network should be able to adjust and find alternate routes for transmitting the information and coordinating the sensing activities.
- Time Synchronization: The distributed sensors collect information for transmission to the local base station. The various sensors should be time synchronized such that the events causing the observation can be correlated and uniquely identified.

- Transceiver frequency: Selection of a suitable RF band for low-power, non-interfering, high-throughput operation is needed.
- Prioritization: The communication between the sensor nodes and the local base station could be synchronous (periodic update messages) or asynchronous (as a result of an anomalous event, which could create a trigger for the monitoring system). The messages sent asynchronously should be allocated higher priority in the network, because of their alert-like nature.
- Hierarchy: The sensor network needs to be organized in an adaptive hierarchy based on the application requirements. The hierarchy among the sensor nodes can ease the routing as well as provide the capability to make distributed decisions. Distributed decisions minimize the transmission of unnecessary raw data to the local base station.
- Information Storage and Retrieval: In the case of communication failure (with the remote central information server) due to inadequate power for communication or interruption in communication link, the sensor network needs to be designed with limited storage capability. This storage capacity can be optimized with respect to the type and number of sensors.
- Protocol Design: Standard communication protocols needs to be customized in order to: (1) Minimize the communication overhead, and (2) Make the sensing system reliable and robust. This customization will provide application oriented network features unique to the continuous monitoring system.

The next generation of the wireless networks for sensor applications needs to be designed accordingly to resolve these important challenges.

1.4 System-on-Chip Design for Smart Sensor Nodes

In order to provide decision making capability and perform complex signal processing at the sensor level, dedicated reconfigurable System-on-Chip (SoC) devices are closely coupled with the micro-electro-mechanical sensors (MEMS). This combined architecture forms the basis of smart sensor nodes.

Reconfigurable devices facilitate fast development time and adaptable architectures for signal processing applications in many domains, including ultrasonic testing and measurements [Rodriguez-Andina *et al.,* 2007]. Until recently, FPGAs were not seriously considered for battery powered sensor applications due to their relatively higher cost and power consumption. Today, various FPGA technologies have significantly different power profiles, and these differences can have a profound impact on the overall system design and power budget. Flash based FPGAs such as Actel IGLOO [ACTEL, 2009] offer ultra-low power consumption with a selection of power management modes to drastically reduce the power requirements while providing programmability and high computation power in small form-factor packages and low cost. Due to the unparalleled adaptability and scalability of FPGAs, they can be re-programmed, designs can be modified, and improved continuously with no extra cost overhead.

Smart sensor nodes can be implemented using low power FPGA devices as shown in Fig. 1.5. In order to meet all the design metrics, optimizations are required at both algorithm level and architectural level. To address this issue, a hardware/software co-design scheme is necessary where an embedded processor core is used for pre-processing and synchronizing the streaming input data from multiple sensors. A point-to-point channel bus is used to perform fast communication between external hardware accelerator blocks and the processor(s) on the FPGA. These accelerator blocks implement the required datapath functions found in signal processing algorithms (i.e., filtering, wavelet transform, and neural networks as described in AE sensing methodology) via specialized Processing Elements (PEs).

Recently, FPGA based ultrasonic signal processing hardware have been successfully used in real-time flaw detection [Weber *et al.,* 2008], ultrasonic data compression [Oruklu *et al.,* 2007] and parameter estimation applications [Lu *et al.,* 2008] demonstrating its versatility. In addition, power and area efficient implementations based on recursive filter structures for subband decomposition have been proposed [Oruklu *et al.*, 2008]. These implementations are especially suitable for ultra-low power smart sensors used in structural monitoring applications.

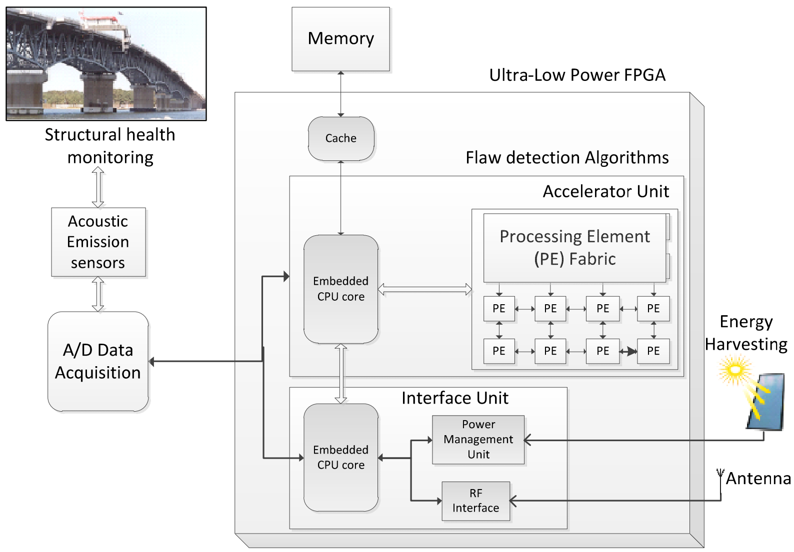

Fig. 1.5. Reconfigurable SoC for sensor nodes in health monitoring applications

1.5 Sustainable Operation of the Wireless Sensor Network

Sensors, data acquisition systems, communication and processing units require sustainable power for truly autonomous operation. Sustainable operation of an intelligent sensor network platform is determined by the interrelation of three metrics: 1) Peak energy consumption of the sensor node components, 2) Energy harvesting/generation capability, and 3) Rechargeable battery capacity. If peak sensor energy consumption can eventually drain the battery, system is deemed not sustainable. Therefore, designing intelligent hardware and software protocols is necessary for achieving energy and service equilibrium to enable the on-going sensing operations. In the following subsections, design decisions for achieving sustainability are highlighted with respect to these metrics.

1.5.1 *Power consumption in structural health monitoring applications*

There are three major components that consume power within the smart sensor nodes: a) RF communication chip; b) smart processing core; and c) sensor analog front-end. Smart sensors not only augment the capabilities for signal processing but also reduce the data communication. This is possible since smart sensors only need to communicate when there is an anomaly or if an interrogation request arrives from the central server. In conventional wireless sensor networks applied to structural monitoring, the sensor nodes are programmed to transmit data periodically for data aggregation, increasing the communication needs significantly. The frequency and size of the transmission is extremely important since most of the energy consumption in wireless sensor networks comes from the RF front-end. Hence, although advanced processors used in the smart sensor nodes may bring additional power requirements, the benefits of reducing the RF transmissions outweigh this increase significantly.

Several standards exist for RF communications such as IEEE 802.11 (WLAN), Bluetooth and IEEE 802.15.4 (ZigBee). Among these standards, ZigBee has become a popular choice in WSN applications due to its low power requirements and adequate data rates (up to 250Kbps). For example, a common chip for ZigBee is Texas Instruments CC2420 2.4 GHz RF transceiver [Texas Instruments, CC2420]. It has been widely used in other smart sensors such as MicaZ and Mica2 [Lynch and Loh, 2006]. The CC2420 transmission power output ranges from -25 dBm to 0 dBm; while the corresponding consumption ranges from 8.5mA to 17.4mA. In receiver mode, the typical current consumption is 19.7 mA. RF chip transmission power output is an important choice for the overall operation of the WSN. Transmission power determines i) the communication distance, ii) current consumption and iii) battery output capacity. Therefore, sensor deployment (i.e. the proximity of the neighboring nodes) for the infrastructure should be done carefully by analyzing the power requirements and sensor node distances. Studies in structural health monitoring applications show that power level -10dBm is sufficient for 20m transmission distance to other nodes while consuming 11.2mA [Linderman et al., 2010] in bridge monitoring.

RF communication consumes significantly more power than sensor frontend or microcontroller units such as Texas Instruments MSP430 which consumes only 330μA while running at 1 MHz. However, distributed computing strategy (associated with smart sensors) for health monitoring requires complex computation and processing [Gao, 2005]. Several new sensor technologies follow this trend such as iMote2 [Kling et al., 2005] which is based on Intel XScale processor running at up to 100 MHz. On the other hand, FPGAs provide reconfigurable logic, tremendous flexibility and dedicated data-path logic for custom data processing. This enables previously unattainable computation and control to be realized at the sensor node. New FPGA technologies target low-power sensor applications with ultra-low power standby and active mode selections. For example, an ACTEL IGLOO FPGA (which contains an ARM Cortex-M1 processor and 250,000 gates) uses a quiescent current of only 24μA [Actel, 2009].

The third major component of the sensor node is the acoustic emission sensor. Acoustic emission sensors are passive devices; they do not need power. However, additional circuitry is necessary to amplify, filter and convert AE signals to digital. All of these operations can be handled by a single analog front-end chip [Texas Instruments, AFE-5801] which has maximum 50mW power consumption at 30 MSPS and supports full power-down and standby modes.

1.5.2 *Energy harvesting*

Among all energy harvesting techniques, solar energy is the most convenient and suitable for structural health monitoring applications. Photovoltaic cells provide the highest power concentration (100 mW/cm2) [Roundy *et al*., 2003] and infrastructures such as bridges can utilize the ambient solar energy by coupling the solar panels and sensor nodes. Another energy source, although limited in power generation, is piezoelectric material in which mechanical strains across a material layer generate a surface charge. Several companies such as Microstrain, Inc.

produce piezoelectric energy harvesters [PVEH, 2011]. These harvesters can produce up to 30mW at 3.2 VDC with 1.5 *g* input vibrations.

Solar and piezoelectric energy harvesters can be simultaneously deployed for redundant and fault-tolerant monitoring operation: The sensors located under direct sunlight are equipped with two sustainable sources: solar and piezoelectric. The system can utilize an intelligent controller to switch between available sources (solar or vibration). For instance, during the daytime -when sun irradiation is plentiful- solar provides the main power not only to power the smart sensors but also to charge up the backup battery. During the night or cloudy situations, the backup battery and the piezoelectric can act as the power source. A multiple-input power electronic converter needs to be implemented to add the energy of both these sources for energy diversification and increased reliability. The combination of various energy sources provides adequate power to energize the sensors and supply the power required for the SoC computation and RF communication.

1.5.3 *Power management*

For sustainability, not only energy harvesting is critical, but also efficient power management is necessary. Power management and maintenance of a reliable operation is ensured by:

- Removing the load from energy harvesting source (putting the SoC system into sleep mode) if power reserves are less than a threshold.
- Minimizing the operations requiring high power consumption such as frequent and/or redundant raw data transmissions.
- Reserving minimum emergency power for critical instances of sensing such as when the traffic load is heavy and/or unexpected severe environmental changes occur.
- Utilizing ultra-low power components with minimal standby current.
- Transmitting only when there is an anomaly or a major change in the structural health to be reported.
- By integrating smart SoC processors, sensor nodes are capable of self-monitoring their power generation and power consumption continuously.

For continuous use, a power reserve must be provided in the form of battery to avoid power shortages. Using rechargeable energy storage such as high capacity (>5000mAh) Li-Ion/Polymer batteries, the power harvested by photovoltaic cells or piezoelectric energy sources can extend over a long period of time.

A sustainable sensor node system for structural health monitoring applications is shown in Fig. 1.6. Here, a power manager and ultra-low voltage step-up converter chip [Linear, LTC3108] is used for harvesting current from the photovoltaic cell or piezoelectric sensors and providing power to smart sensor node and wireless transmitter chips. In addition, harvested current can be diverted to recharging the battery during stand-by mode, in order to power the system when the energy harvesting source is insufficient. For charging Li-Ion/Polymer batteries, a battery charger system [Linear, LTC4070] is used. This charger is optimized for intermittent or continuous charging sources, making it ideal for energy harvesting.

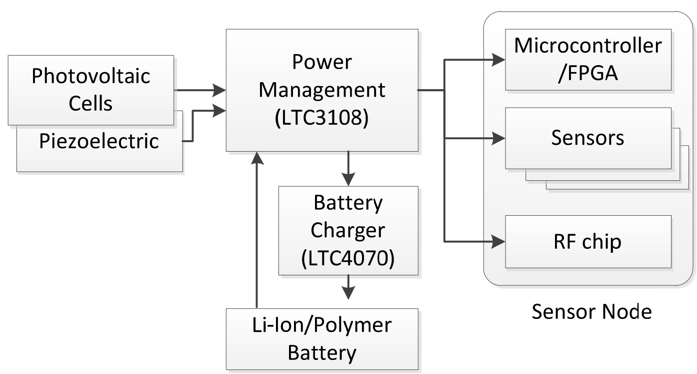

Fig. 1.6. Sustainable smart sensor nodes

1.6 Further Information

More information in this topic can be found in the journal publications; Structural Health Monitoring, An International Journal; NDT&E International; IEEE Sensors Journal; IEEE Transactions on Mobile Computing; IEEE Transactions on Ultrasonics, Ferroelectrics and

Frequency Control; Journal of the Acoustical Society of America; and in the proceedings of IEEE Sensors; IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON); International Conference on Information Processing in Sensor Networks (IPSN); and IEEE Ultrasonics Symposium.

1.7 Conclusion

A major challenge facing our society is the rapidly aging infrastructure. The funds needed to reconstruct infrastructure systems and to maintain their service at a level that is considered satisfactory are prohibitive. Therefore, it is imperative that any planning for reconstruction should specifically look into a prioritization scheme. The availability of a versatile and smart monitoring system, with ability to provide information on structural health conditions on a routine basis, will substantially enhance the capabilities of various agencies when they plan for prioritizing their infrastructure systems for maintenance.

Many structural health monitoring systems that are available today are only applicable to specific structures and lack the versatility needed to cover a whole host of distress conditions. To address these shortcomings, implementation of structural health monitoring systems should include:

- Design and realization of application oriented network for wireless communication.
- Design and realization of smart computing engines in the sensor nodes for on-going real-time monitoring.
- Design and realization of power harvesting and power usage optimization for self-sustainable operation.
- Design and synthesis of advanced signal processing algorithms for defect detection and characterization.
- Data archiving and analysis for damage assessment and maintenance scheduling.

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