LA-UR-07-0365, ASCE Journal of Infrastructure Systems, Vol. 14 (1), pp. 64-79, 2008

Energy Harvesting for Structural Health Monitoring Sensor Networks

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ABSTRACT

This paper reviews the development of energy harvesting for low-power embedded structural health monitoring (SHM) sensing systems. A statistical pattern recognition paradigm for SHM is first presented and the concept of energy harvesting for embedded sensing systems is addressed with respect to the data acquisition portion of this paradigm. Next, various existing and emerging sensing modalities used for SHM and their respective power requirements are summarized followed by a discussion of SHM sensor network paradigms, power requirements for these networks and power optimization strategies. Various approaches to energy harvesting and energy storage are discussed and limitations associated with the current technology are addressed. The paper concludes by defining some future research directions that are aimed at transitioning the concept of energy harvesting for embedded SHM sensing systems from laboratory research to field-deployed engineering prototypes. Finally, it is noted that much of the technologies discussed herein is applicable to powering any type of low-power embedded sensing system regardless of the application.

INTRODUCTION

Structural health monitoring (SHM) is the process of detecting damage in aerospace, civil, and mechanical infrastructure. The goal of SHM is to improve the safety, reliability, and/or ownership costs of engineering systems by autonomously monitoring the conditions of structures and detecting damage before it reaches a critical state. To achieve this goal, technology is being developed to replace qualitative visual inspection and time-based maintenance procedures with more quantifiable and automated condition-based damage assessment processes. The authors believe that all approaches to SHM, as well as all traditional non-destructive evaluation procedures can be cast in the context of a statistical pattern recognition problem [1,2,3]. Solutions to this problem require the four steps of 1. Operational evaluation, 2. Data acquisition, 3. Feature extraction, and 4. Statistical modeling for feature classification. Inherent in parts 2-4 of this paradigm are the processes of data normalization, data compression and data fusion. Here data normalization refers to the process of separating changes in a measured system response caused by varying operational and environmental conditions from changes caused by damage [4].

As the sensor network hardware evolves, the possibility of embedding these networks in all types of aerospace, civil, and mechanical infrastructure is becoming both technically and economically feasible. However, the concept of "embedded" sensing can not be fully realized if the systems will require cables to access to traditional power sources or if batteries have to be periodically replaced. Therefore, there is a need to harvest and store ambient sources of energy in an effort to make these embedded systems as autonomous as possible. Although energy harvesting for large-scale alternative energy generation using wind turbines and solar cells is mature technology, the development of energy harvesting technology on a scale appropriate for small, low-power, embedded sensing systems is still in the developmental stages, particularly when applied to SHM sensing systems.

This paper will summarize the state-of-the–art in energy harvesting as it has been applied to SHM embedded sensing systems. First, various existing and emerging sensing modalities used for SHM and their respective power requirements are summarized followed by a discussion of SHM sensor network paradigms, power requirements for these networks and power optimization strategies. Various approaches to energy harvesting and energy storage are then discussed and limitations associated with the current technology are addressed. This discussion also addresses current SHM energy harvesting applications and system integration issues.

SENSING SYSTEM DESIGN CONSIDERATIONS FOR SHM

Once the operational evaluation portion of the SHM paradigm has defined damage to be detected, one must then establish an appropriate sensor network that can adequately observe changes in the system dynamics caused by damage and manage these data for suitable signal processing, feature extraction and classification. The goal of any SHM sensor network is to make the sensor reading as directly correlated with, and as sensitive to, damage as possible. At the same time, one also strives to make the sensors as independent as possible from all other sources of environmental and operational variability, and, in fact, independent from each other (in an information sense) to provide maximal data with minimal sensor array outlay. To best meet these goals, the following design parameters must be defined, as much as possible, *a priori*: types of data to be acquired; sensor types, number and locations; bandwidth, sensitivity and dynamic range; data acquisition/telemetry/storage system; power requirements; sampling intervals; processor/memory requirements; and excitation source needs (for active sensing).

Fundamentally, there are five issues that control the selection of hardware to address these sensor system design parameters: (i) the length scales on which damage is to be detected; (ii) the time scale on which damage evolves; (iii) effect of varying and/or adverse operational and environmental conditions on the sensing system; (iv) power availability;, and (v) cost. In addition, the feature extraction, data normalization and statistical modeling portions of the SHM process can greatly influence the definition of the sensing system properties.

With these design parameters and issues in mind, the sensing systems for SHM that have evolved to date consist of some or all of the following components: transducers that convert changes in the field variable of interest to changes in an electrical signal; actuators that can be used to apply a prescribed input to the system; analog-to-digital (A/D) and digital-to-analog (D/A) converters; signal conditioning; power; telemetry; processing capability; and Memory for data storage.

Current SHM Sensor Modalities

The sensing component (transducer) refers to the transduction mechanism that converts a physical field (such as acceleration) into an electronically measurable form (usually an electrical potential difference). If the sensing system involves actuation, then the opposite is required, i.e., a voltage command is converted into a physical field (usually displacement). The most common measurements *currently* made for SHM purposes are, in order of use: acceleration, strain, Lamb wave, and electrical impedance.

Acceleration

Making local acceleration measurements using some form of accelerometer is by far the most common approach used in SHM applications today. This situation is primarily the result of the relative maturity and commercial availability of accelerometer hardware and associated signal conditioning hardware. These accelerometers, which use a variety of different transduction mechanisms (e.g. piezoelectric, piezoresistive, capacitance) are designed to be used within a conventional wired network, and each individual sensor output voltage must be transferred to a centralized data acquisition unit containing appropriate charge amplification, analog-to-digital converters, signal processing (e.g., anti-aliasing filtering), and demultiplexing. The energy consumed by these devices themselves is very small because of their passive nature, but the centralized multiplexing, amplification, and signal conditioning units required to obtain usable data can often have power requirements that approach 1 W. A typical 4-channel power supply delivers 3-30 mA of current at 30 V, equating to 0.9 W in the largest case; power requirements go up with large channel counts so that very large (~100) accelerometer arrays may have power requirements measuring tens of watts. In addition, there is considerable recent work suggesting the use of micro-electromechanical systems (MEMS) accelerometers for SHM applications, but to date this type of accelerometer has seen little actual use in SHM applications.

Strain

Second to measurements of acceleration for SHM is the measurement of strain. Like accelerometers, strain gages are a mature technology. The most common strain gage technology is the electric resistive foil gage. These systems, including signal conditioning, consume power at a level very commensurate with piezoelectric accelerometers; typically about 1 W for 3-4 channels, although the number depends on the specific input impedance of the bridge circuit being used.

Although foil resistive gages dominate current market usage, the last several years have witnessed a significant increase in commercially-available fiber optic solutions to strain measurement. The two dominant fiber optic technologies are direct fiber interferometry and fiber Bragg gratings (FBGs) [5]. Most commercial systems today take advantage of FBG technology [6]. Power requirements for fiber optic systems are usually larger than for conventional strain gage systems. The largest power consumer in the fiber strain sensing system is the thermoelectric cooler, which can use energy at the rate of approximately 3-5 W, depending on control demands imposed by the environment. The filter and SLED optical source used typically operate at power levels below 1 W.

Piezoelectric Patches for Sensing and Actuation

Most wave propagation approaches to SHM make use of piezoelectric patches as both sensors and actuators. The piezoelectric effect works in two ways. When used as a sensor, the patches utilize the direct effect where a charge being produced when the material is strained. However, the converse effect is also true: when a voltage is applied to the material, the material will deform proportionally to the applied potential difference, and this allows such materials to be used as an actuator (converse effect). Arrays of these devices can be configured to sequentially induce local motion at various locations on the structure, and the same array can also be used to measure the response to these excitations. In this mode the sensor-actuator pairs interrogate a structure in a manner analogous to traditional pitch-catch or pulse-echo ultrasonic inspection. Alternatively, many researchers have measured the electrical impedance across a piezoelectric patch as an indictor of damage [7]. It has been shown that this electrical impedance is related to the local mechanical impedance of the structure, with the assumption that the mechanical impedance will be altered by damage.

In the passive sensing mode, piezoelectric transducers would consume much less energy, compared to accelerometers or strain gauges, because they do not require any electrical peripherals such as signal conditioning and amplification units which are typically embedded and required for piezoelectric accelerometers to operate. However, this low power consumption characteristic will be modified if one needs to use charge amplifiers or voltage follower circuits to improve the signal-to-noise ratio depending on applications or frequency range of interest. When used in an active sensing mode, a digital-to-analog converter (D/A) and a waveform generator are also needed along with higher speed A/D converters, additional memory, and possibly multiplexers in order to control and manage a network of piezoelectric transducers. These extra components will inherently demand more energy.

Current SHM Sensor Network Strategies

Based on these sensing modalities and the sensing system design parameters and issues discussed above, two general sensor network paradigms have evolved in the SHM field.

Sensor arrays directly connected to central processing hardware

Figure 1 shows a sensor network directly connected to the central processing hardware. Such a system is the most commonly used scheme for structural health monitoring studies. The advantage of this system is the wide variety of commercially available off-the-shelf systems that can be used for this type of monitoring and the wide variety of transducers that can typically be interfaced with such a system. For SHM applications, these systems have been used in both a passive and active sensing manner. Limitations of such systems arise because they are difficult to deploy in a retrofit mode because they usually require AC power, which is not always available. Also, the direct wired connections to the processing unit make these systems one-point failure sensitive, as one wire may be as long as a few hundred meters.

There are a wide variety of such systems. At one extreme is peak-strain or peak-acceleration sensing devices that notify the user when a certain threshold in the measured quantity has been exceeded. A more sophisticated system often used for condition monitoring of rotating machinery is a piezoelectric accelerometer with built-in charge amplifier connected directly to a hand-held, single-channel fast-Fourier-transform (FFT) analyzer. Here the central data storage and analysis facility is the hand-held FFT analyzer. Such systems cost on the order of a few thousand dollars. At the other extreme is custom designed systems with hundred of data channels containing numerous types of sensors that cost on the order of multiple millions of dollars such as that deployed on the Tsing Ma bridge in China [8]. One active wired system that has been specifically designed for SHM applications consists of an array of peizoelectric patches embedded in Mylar sheet that is bonded to a structure [9].

Wireless Decentralized Sensing and Processing

The integration of wireless communication technologies into SHM methods has been widely investigated in order to overcome the limitations of wired sensing networks. Wireless communication can remedy the cabling problem of the traditional monitoring system and significantly reduce the maintenance cost. The schematic of the de-centralized wireless monitoring system is shown in Figure 2.

From the large-scale SHM practice, however, several very serious issues arise with the current design and deployment scheme of the decentralized wireless sensing networks [10,11]. First, the current wireless sensing design usually adopts ad-hoc networking and hopping that results in a problem referred to as data collision, where a network device receives several simultaneous requests to store or retrieve data from other devices on the network. Nodes near the centralized base station are susceptible to data collision and because most data flows through these nodes, they will use up any battery power faster than the remote nodes. In addition, this decentralized wireless sensing network scales poorly in active-sensing system deployment. Descriptions of wireless SHM sensor networks can be found in Tanner *et al.*, [12] where the authors adapted an SHM algorithm to the limitations of off-the-shelf wireless sensing and data processing hardware. Lynch *et al.* [10] and Lynch and Loh [13] summarize a study where the investigators have developed a wireless SHM system. Spencer *et al.* [11] provides the state-of-the-art review of current "smart sensing" technologies that includes the compiled summaries of wireless work in the SHM field using small, integrated sensor, and processor systems. To implement computationally intensive SHM processes, Farrar *et al*. [14] selected a single board computer coupled with a wireless networking capability as a compact form of true processing power. Finally, researchers are developing hybrid connection network that advantageously combines the wired and wireless networks, as discussed by Dove *et al.* [15].

Practical Implementation Issues for SHM Sensing Networks

A major concern with these current sensing networks is their long-term reliability and sources of power. If the only way to provide power is by direct connections, then the need for wireless protocols is eliminated, as the cabled power link can also be used for the transmission of data. However, if one elects to use a wireless network, the development of micro-power generators is a key factor for the deployment of this hardware. A possible solution to the problem of localized power generation is technologies that enable harvesting ambient energy to power the instrumentation. Forms of energy that may be harvested include thermal, vibration, acoustic, and solar. The rest of this paper will discuss approaches to minimizing the energy demands of a sensor network and strategies to harvest ambient energy in an effort to power these sensing systems.

ENERGY DEMANDS ASSOCIATED WITH SHM SENSING SYSTEMS

Embedded system design is characterized by a tradeoff between a need for good performance and low power consumption. Proliferation of wireless sensing devices has stressed even more the need for energy minimization as the battery capacity has improved very slowly (by a factor of 2 to 4 over the last 30 years), while the computational demands have drastically increased over the same time frame, as shown in Figure 3.

Since the introduction of wireless computing, the demands on the battery lifetime have grown even more. In fact, in most of today's embedded sensing devices, the wireless connectivity consumes a large fraction of the overall energy consumption. Figure 4 shows a power consumption breakdown for a small sensor node (top of the figure) and a larger embedded device based on a Strong ARM processor (200 MHz) coupled with a wireless local area network (WLAN) for communication. On small sensor nodes, as much as 90% of the overall system power consumption can go to wireless communication, while on the larger devices, such as the one shown at the bottom of the Figure 4, the wireless takes approximately 50% of the overall power budget. In both cases, the second most power-hungry device is the processor. Therefore, in order to achieve long battery lifetimes, both optimization of both computing and communication energy consumption are critically important.

Better low-power circuit design techniques have helped to lower the power consumption [16,17,18]. On the other hand, managing power dissipation at higher levels can considerably decrease energy requirements and thus increase battery lifetime and lower packaging and cooling costs [19,20]. Two different approaches for lowering the power consumption at the system level have been proposed: dynamic voltage scaling, primarily targeted at the processing elements, and dynamic power management, which can be applied to all system components. The rest of this section provides an overview of state-of-the-art dynamic power management and dynamic voltage scaling algorithms that can be used to reduce the power consumption of both processing and communication in wireless sensing devices.

Dynamic Voltage Scaling

Embedded sensing systems are designed to be able to deliver peak performance when needed, but most of the time, their components operate at utilizations less than 100%. One way of lowering the power consumption is by slowing down the execution, and, when appropriate, also lowering the component's voltage of operation. This power reduction is done with *dynamic Voltage Scaling (DVS)* algorithms.

$$P_{dyn} \propto f\, V_{dd}^{\;2} \qquad (1)$$

$$f \propto (V_{dd} - V_{treshold})^2 / V_{dd} \qquad (2)$$

The primary motivation comes from the observation that dynamic power consumption, P_{dyn}, is directly proportional to the frequency of operation, f, and the square of the supply voltage, V_{dd}^2 (see Equation (1)). Frequency, in turn, is a linear function of V_{dd}, (see Equation (2)), so decreasing the voltage results in a cubic decrease in the power consumption. Clearly, decreasing the voltage also lowers the frequency of operation, which, in turn, lowers the performance of the design. Figure 5 shows the effect of DVS on power and performance of a processor. Instead of having longer idle period, the central processing unit (CPU) is slowed down to the point where it completes the task in time for the arrival of the next processing request while at the same time saving quite a bit of energy. DVS algorithms are typically implemented at the level of an operating system's (OS) scheduler. There have been a number of voltage scaling techniques proposed for real-time systems. Early work typically assumed that the tasks run at their worst case execution time (WCET), while the later research work relaxes this assumption and suggest a number of heuristics for prediction of task execution time. A more detailed overview on various DVS algorithms can be found in [21].

Dynamic Power Management

In contrast to DVS, system-level *dynamic power management (DPM)* decreases the energy consumption by selectively placing idle components into lower power states. DVS can only be applied to CPUs, while DPM can be used to reduce the energy consumption of wireless communication, CPUs and all other components that have low power states. While slowing down the CPU with DVS can provide quite a bit of power savings, applying DPM typically increases the savings by at least a factor of 10, and in many systems by significantly more than that. On the other hand, changing processor speed happens relatively quickly, while the transitions in and out of sleep states can be quite costly in terms of both energy and performance. Figure 6 shows both power and performance overheads incurred during the transition. At a minimum the device needs to stay in the low-power state for long enough (defined as the break even time, T_{BE}) to recuperate the cost of transitioning. The break even time, as defined in Equation (3), is a function of the power consumption in the active state, P_{on}, the amount of power consumed in the low power state, P_{sleep}, and the cost of the transition in terms of both time, T_{tr}, and power, P_{pr}.

$$T_{BE} = T_{tr} + T_{tr} \frac{P_{tr} - P_{on}}{P_{on} - P_{sleep}} \tag{3}$$

If it were possible to predict ahead of time the exact length of each idle period, then the ideal power management policy would place a device in the sleep state only when an idle period would be longer than the break-even time. Unfortunately, in most real systems such perfect prediction of idle periods is not possible. As a result, one of the primary tasks DPM algorithms have is to predict when the idle period will be long enough to amortize the cost of transition to a low power state, and to select the state to transition to. Three classes of policies can be defined – timeout based, predictive, and stochastic. Timeout policy is implemented in most operating systems. The drawback of this policy is that it wastes power while waiting for the timeout to expire. Predictive policies developed for interactive terminals [22,23] force the transition to a low power state as soon as a component becomes idle if the predictor estimates that the idle period will last long enough. An incorrect estimate can cause both performance and energy penalties. Both timeout and predictive policies are heuristic in nature, and thus do not guarantee optimal results. In contrast, approaches based on stochastic models can guarantee optimal results. Stochastic models use distributions to describe the times between arrivals of user requests (*interarrival times*), the length of time it takes for a device to service a user's request, and the time it takes for the device to transition between its power states. The optimality of stochastic approaches depends on the accuracy of the system model and the algorithm used to compute the solution.

Finally, much recent work has looked at combining DVS and DPM into a single power management implementation. Shorter idle periods are more amiable to DVS, while longer ones are more appropriate for DPM. Thus, a combination of the two approaches is needed for the most optimal results. It should also be pointed out that the studies in the current SHM sensing hardware development [11,13] have not yet incorporated the power-awareness design described in this section.

ENERGY HARVESTING METHODS AND APPLICATIONS FOR SHM

The process of extracting energy from the environment or from a surrounding system and converting it to useable electrical energy is known as *energy harvesting*. Recently, there has been a surge of research in the area of energy harvesting. This increase in research has been brought on by the modern advances in wireless technology and low-power electronics. Given the wireless nature of some emerging sensors, it becomes necessary that they contain their own power supply, which is, in most cases, conventional batteries. However, when the battery has consumed all of its power, the sensor must be retrieved and the battery replaced. Because of the remote placement of these devices, obtaining the sensor simply to replace the battery can become a very expensive and tedious, or even impossible, task. If ambient energy in the surrounding medium can be obtained and utilized, this captured energy can then be used to prolong the life of the power supply or, ideally, provide unlimited energy for the lifespan of the electronic device. Given these reasons, the amount of research devoted to energy harvesting has been rapidly increasing, and the SHM and sensing network community have investigated the energy harvesters as an alternative power source for the next generation of embedded sensing systems.

The sources of typical ambient energies are sunlight, thermal gradient, human motion and body heat, vibration, and ambient RF energy. Several excellent articles reviewing the possible energy sources for energy harvesting can be found in the literature [24, 25, 26, 27, 28, 29, 30]. Fry *et al*. [24] provides an overview of portable electric power sources that meet the US military special operation requirements. The report defines a list of general attributes intended to suggest what a standard characterization of different portable energy supplies should include. The list includes Electrical (energy density, total energy content, power density, maximum voltage and current, RF emission power, electrical interconnects), Physical (size/shape, weight), Environmental (acoustic emission power, mechanical shock tolerance, electrical shock tolerance, water resistance, operating temperature range), Operational (energy requirements for recharging, orientation), Maintenance (testing requirements), Safety, and Disposal.

Roundy [26] compares the energy density of available and portable energy sources, shown in

Table 4. He concludes that, for a device whose desired lifetime is in the range of 1 year or less, battery technology alone is sufficient to provide enough energy. However, if a device requires a longer service life, which is often the case, then an energy harvester can provide a better solution than the battery technologies. Paradiso and Starner [30] also provide the energy harvesting capabilities of different sources, shown in

Table 5, which are slightly different from those suggested by Roundy [26]. Glynne-Fones and White[25], Qiwai *et al*. [27], Sodano *et al*. [28] and Mateu and Moll [29] summarized the basic principles and components of energy harvesting techniques, including piezoelectric, electrostatic, magnetic induction, and thermal energy. A common suggestion listed in these articles is the combined use of several energy harvesting strategies in the same devices so that the harvesting capabilities in many different situations and applications can be increased.

The purpose of this section is to provide an up-to-date assessment of available energy harvesting methods suitable for potential SHM sensing applications. This section is not intended to provide an exhaustive literature survey, as this area is very broad and useful review articles are already available in the literature. Instead, this section will provide a concise introductory survey on the topic and outline the current status of energy harvesting as applied to relevant themes in SHM.

Converting Mechanical Vibration to Electrical Energy

One of the most effective methods of implementing an energy harvesting system is to use mechanical vibration to apply strain energy to a piezoelectric material or to displace to an electromagnetic coil. Energy generation from mechanical vibration usually uses ambient vibration around the energy harvesting device as an energy source, and then converts it into useful electrical energy. The concept of utilizing piezoelectric material for energy generation has been studied by many researchers over the past few decades. Piezoelectric materials form transducers that are able to interchange electrical energy and mechanical motion or force. These materials, therefore, can be used as mechanisms to transfer ambient vibration into electrical energy that may be stored and used to power other devices. Overviews of the application of piezoelectric transducers as energy harvesters has been recently given by Sodano *et al*. [28] and duToit *et al*. [31].

One early study into energy harvesting by Kymissis *et al.* [32] developed a piezoelectric system that would harvest the energy lost during walking and used it to power a radio transmitter, shown in Figure 7. The devices that were considered included a Thunder actuator constructed of piezoceramic composite material located in the heel and a multilayer PVDF foil laminate patch located in the sole of the shoe. The average power generated from both the PVDF and the Thunder actuator was estimated approximately 1 mW and 2 mW, respectively, shown in the figure. It was also found that the two piezoelectric devices used produced sufficient energy to power a transmitter that could send a 12-bit radio frequency identification code every 3-6 steps. Another investigation into the ability to use piezoelectric materials for power harvesting from the motion of humans and animals, was performed by Ramsey and Clark [33], who studied the ability to power an *in vivo* MEMS application. The research used a thin square plate driven by blood pressure to provide energy and was shown to be capable of powering the electronics if they were used intermittently. Although these wearable energy harvesters are not suitable for powering SHM sensor nodes, these works demonstrated the feasibility of using the piezoelectric-base harvested energy for wirelessly transmitting data and subsequently gained the attention of many researchers in the area of self-powered wireless sensors.

Sodano et al. [34] estimated the power output from a piezoelectric cantilever auxiliary structure attached to an automobile compressor. A 40 x 62 mm piezoelectric patch mounted to a fixed-free, 40 x 80 mm plate was able to charge a 40 mAh button cell battery in one hour. Sodano et al. [35] also formulated a model of a power harvesting system that consisted of a cantilever beam with piezoelectric patches attached. The model was verified on a cantilever beam experiencing a base excitation from the clamped condition. The model was found to accurately estimate the energy generated and was also used to demonstrate the damping effect of a piezoelectric energy harvester. The development of an accurate analytical model to estimate the power output from the piezoelectric transducers and to understand the effects of several components, including mechanical and electrical loads and electrical circuit parameters, has received considerable attention by energy harvesting researchers. As such, various efforts on analytical modeling and analysis of piezoelectric energy harvesting can be found in the literature [31, 36, 37, 38, 39, 40].

The efficiency of the piezoelectric material in a stack configuration for the purpose of electric energy generation was analyzed Goldfarb and Jones [41]. It is suggested that the maximum efficiency of power generation can be achieved by minimizing the amount of energy stored inside the piezoelectric material. Although the piezoelectric stack utilizes the higher electromechanical coupling mode (d_{33}) compared to that of the patch configuration (d_{31}), the patch configuration holds great advantages in energy conversion because the excitation is more easily achieved by environmental sources [29, 33]. Accordingly, a cantilever beam with the piezoelectric patches attached in either a unimorph or a bimorph form is the most common configuration for energy harvesting. Others utilized the shape of membranes under pressure loading [39,42], and plates with a Helmholtz resonator under fluid/acoustic loading [43].

Recently, the development of MEMS-scale micro power generator has received considerable attention, as piezoelectric materials are suitable for micro-fabrication [31, 44,45, 46]. For instance, the micro-scale piezoelectric harvester developed by Jeon *et al*. [45], shown in Figure 8, generated a maximum DC voltage of 3 V and a maximum continuous electrical power of 1 μW under the first resonance frequency excitation.

Other than traditional piezoceramic and PVDF materials, several researchers have investigated the energy harvesting performance of Lead Magnesium Niobate-Lead Titanate (PMN-PT) single crystal devices [36, 47], a Macro-Fiber Composite actuator [34], and a "cymbal" piezoelectric transducer [48], which all exhibit higher electromechanical coupling properties than those of traditional transducers and hence show better performance. For instance, a cymbal transducer with a 29 mm diameter and 1 mm thickness produced 39 mW power at a frequency of 100 Hz, which is much higher than values reported in the literature from traditional piezoelectric materials [48].

To achieve higher efficiency, it is necessary to match the resonance frequency of the transducer with the most distinct frequency of the vibration source. Cornwell *et al.* [49] adjusted various mechanical parameters, including the resonant frequency and the location of a harvester, in order to maximize the strain induced in the piezoelectric element and to improve power output. The power generation was increased by a factor of 25, when the frequency of the harvesting device was well-tuned to that of the structure. Roundy and Wright [38] also suggested the same resonance excitation concept. The proof mass was used to maximize the power output, shown in **Error! Reference source not found.**. The vibration present in a structure is, however, usually much lower than the resonance of a harvesting device and often changes during operation; therefore, this vibration does not always effectively couple energy to the harvester. The optimization of the transducer setup and geometry is one of the most challenging tasks during the design, but it has received less attention from researchers [37].

With respect to ambient vibration, there is another possible way of converting mechanical energy into electricity. The electromagnetic systems are composed of a coil and a permanent magnet attached to a spring. The mechanical movement of the magnet, which is caused by structural vibration, induces a voltage at the coil terminal and this energy can be delivered to an electrical load. The amount of power produced is maximum at resonance of a device and proportional to the square of the peak mass displacement [29]. Furthermore, a large proof mass (a magnet) with large coil areas will perform better than smaller ones, although the size and displacement will be limited by the spring and the housing of the device.

Williams and Yates [50] proposed a device that generates electricity using an electromagnetic transducer. It was determined that the amount of power generated was proportional to the cube of the vibration frequency. Yuen *et al.* [51] developed an electromagnetic-based micro energy converter that can be packaged into an AA battery-size container. The device was used to serve as a power supply for a wireless temperature sensing system. Glynne-Jones *et al.* [52] designed a miniature electromagnetic power generator, shown in

Figure **10**, which is based around four magnets coupled to a cantilevered coil. The device, with a volume of 3.15 cm^3, could produce a peak power of 3.9 mW with an average power of 157 μW, when mounted on the engine block of the car. Mizuno and Chetwynd [53] also investigated an electromagnetic micro generator with a predicted power output of 6 nW for a typical single-element generator. The authors suggested deploying a “stacked” array configuration to increase the output. Recently Stephen [54] has analyzed the dynamics of an electromagnetic energy generator in detail. He concluded that the maximum power is delivered when the resistance of an electrical load is equal to the sum of the coil internal resistance and the electrical analogue of the mechanical damping coefficient.

Poulin *et al*. [55] presented a comparative study of electromagnetic and piezoelectric energy conversion systems. These authors found that the two systems are in complete duality in every respect, some elements shown in

Table 6. The authors suggested that the piezoelectric system is well-suited to energy generation for microsystems because of the higher power density, and they recommended electromagnetic systems for medium scale applications. Roundy [56] pointed out that, although there have been many publications in energy harvesting, a solid basis for comparison between basic technologies has not been well-documented. He concluded that, in addition to the input vibration, the power output depends on the system coupling coefficient, the quality factor of the device, the mass density of the generator, and the degree to which the electrical load maximizes the power transmission. duToit *et al*. [31] summarized some experimental and analytical results on vibration-based energy harvesting devices published in the literature. The device sizes vary from micro (0.01 cm^3) to macro scale (75 cm^3), and the energy generated ranges from 1 μW to a few mW. However, they conclude that it is a somewhat daunting task to compare the performance of different energy harvesting systems because they use different energy conversion schemes, they have different input frequency spectra, and the various systems and structures that harvesters were installed in. These parameters are not always documented in the published papers. The authors suggested that the power density (W/cm^3 or W/kg) or the efficiency parameter would be good indicators for comparing the performance of each device.

Because vibration-based energy harvesters are still under the development stage, only a few commercial solutions are available. Most research efforts are still in proof-of-concept demonstrations in a laboratory setting. Microstrain, Inc. [57] developed a prototype of piezoelectric-based energy harvester, shown in **Error! Reference source not found.**. The sensor node is equipped with temperature and humidity sensors with wireless telemetry. It is claimed that the piezoelectric harvester can produce up to 2.7 mW of instant power at 57 Hz vibration. Perpetuum, Inc. [58] commercialized electromagnetic energy converters, which are capable of generating up to 3.3 V and 5 mW of instant power under the 100 mg vibration. The operating frequencies could be tuned in the range of 47-100 Hz. Ferro Solution, Inc. [59] also produced electromagnetic generators that have a 9.3 mW power capability with 100 mg input vibration.

Converting Thermal Energy to Electrical Energy,

A second method of obtaining energy from ambient sources is through the use of thermoelectric generators that capitalize on thermal gradients. Thermoelectric generators (TEGs) use the Seebeck effect, shown in **Error! Reference source not found.**, which describes the effect of the current generated when the junction of two dissimilar metals experiences a temperature difference. Using this principle, numerous p-type and n-type junctions are arranged electrically in series and thermally in parallel to construct the TEG.

Thermoelectric generators have been used for capturing ambient energy in various applications. Lawrence and Snyder [60] suggest a potential method of retrieving electrical energy from the temperature difference that exists between the soil and the air. The results showed that a maximum instantaneous power of approximately 0.4 mW could be generated. Rowe *et al*. [61] investigate the ability to construct a large thermoelectric generator capable of supplying 100 watts of power from hot waste water. The system tested used numerous thermoelectric devices placed between two cambers, one with flowing hot water and the other with cold water flowing in the opposite direction, thus maximizing the heat exchange. Fleming *et al*. [62] investigated the use of TEG for powering micro-scale air vehicles. A TEG was mounted on the exhaust system of an internal combustion engine that was shown to generate 380 mW of power. Several authors have studied the use of thermoelectric generators for obtaining waste energy from the exhaust of automobiles, which are well-summarized in Vázquez *et al*. [63].

The idea to use thermoelectric devices to capture ambient energy from a system is not a new concept. However, in many cases, the research efforts utilize liquid heat exchangers or forced convection that significantly improves heat flow and power generation, but requires complex cooling loops and systems. Therefore, Sodano *et al.* [64] investigated the use of TEGs as power harvesting devices that do not have an active heat exchanger, but function as a completely passive power scavenging system, utilizing solar radiation and harvesting of waste heat. The results showed that the thermoelectric generator produces significantly more power than a piezoelectric device and that the charge time needed to recharge a battery is significantly lower.

The TEG is a mature technology and a reliable energy converter with no moving parts compared to vibration-based harvesters. The TEG has been actively studied for the last three decades and the literature in this area is extensive. One of the drawbacks of this technology is low efficiency (<5 %) if there is a small temperature gradient present. Further, the fabrication cost is high, and the volume and weight are still too large for micro-scale sensing systems. Therefore, with the recent advances made in nano technologies, the fabrication of MEMS-scale TEG devices have been actively studied [65,66,67].

It is worthwhile to note that the TEGs have long been used in NASA space vehicles, such as the Voyager and Cassini probes, as sunlight is not always available for vehicles traveling to the outer reaches of the solar system and beyond. These vehicles use heat generated by the decay of radioactive materials (e.g., plutonium-238) to produce electricity using the TEG. These systems can generate high power in the few watts to kilowatts range for over a decade. However, these devices do not find their use in low-power applications because of difficulties in maintaining the necessary temperature gradient and efficiency for TEGs as the radioactive material's size decreases. For micro-scale applications using radioactive material sources, such as tritium, two different harvesting approaches have been proposed. One approach is using the beta-voltaic effect, which works much like a solar cell [68]. Although the beta-voltaic effect suffers from low efficiencies, Sun *et al*. [69] improved the efficiency by a factor of ten with a new wafer design that provides more reactive surface to interact with the decay particles. Their commercial product, called *Betabatt*, can provide an energy density of 125 μW/cm^3 for 12-20 years [70]. Another approach commonly employed with micro-scale radioactive power sources to harness energy is to combine the radioactive materials with a piezoelectric harvester. Such systems are referred to as a radioisotope-powered piezoelectric generator [71,72]. The principle behind this technique is to capture the kinetic energy of particles emitted by radioactive materials to actuate a piezoelectric cantilever beam that produces electricity in the range of tens of μW. With the overall conversion efficiency of 4 %, their device, called a "nuclear micro-battery," with 10 mg of polonium-210 contained in a 1-cm^3 housing can produce 50 mW of electric power.

Although there will be public perception concerns with regards to environmental and safety issues for such devices, there is a precedent for using these materials in common household and office devices such as smoke detectors and illuminated signs. Currently, research efforts associated with small-scale radioactive energy harvesting devices focus on reducing the cost and improving the efficiency. The atomic batteries have potential applications in MEMS devices, SHM embedded sensing networks, or human medical sensing applications.

RF Wireless Energy Transmission

Another way of supplying power to sensor networks is that of wireless energy transmission. In this case, power is generated elsewhere and transmitted to a sensor node by some form of electromagnetic wave or RF radiation. A pair of excellent survey articles was written to discuss the history of microwave power [73,74]. With the use of rectennas (rectifying-antenna) that integrates the technology to receive and to directly convert the microwaves into DC power, efficiencies in the 50-80% range have been achieved. Significant testing has also been done across long distances and with kW power levels [75]. Briles *et al*. [76] invented a RF wireless energy delivery system for underground gas or oil recovery pipes. The RF energy is generated on the surface, and travels through the conductive pipe acting as an antenna or a waveguide. The sensor module in the bottom of the pipe captures this energy and uses it to power the electrical equipment. A schematic of this concept is shown in **Error! Reference source not found.**. With a 100W transmitted power from the surface, it was estimated that around 48 mW of instant power could be delivered after traveling a 1.6 km along pipe.

Current research efforts in RF wireless energy transmission focus on improving the conversion efficiency and attempt to maximize the output power by designing efficient antennas and rectannas. In particular, circular polarized antennas are being implemented in the rectenna design because it avoids the directionality of other antenna designs [77,78,79]. An array of rectennas is increasingly used to improve the output power [80] and several new rectena design schemes are proposed [81,82]. Different elements are also used for efficient rectification [83,84] in attempt to obtain optimum output power, and these research trends are similar to those typically pursued in the energy harvesting arena.

Originally considered for alleviating the wiring harness in space structures or providing an extremely low power for those typically used in RFID tags in the 1-100 μW range, the application of an RF wireless energy transmission system for powering electronics typically used in distributed sensing networks has not been studied substantially in the past. Therefore, a new SHM sensing network proposed by UCSD and LANL researchers integrates an energy transmission between the host and sensor node and uses this energy to both power the SHM sensing node and to transmit the signal back to the host was proposed [85]. They experimentally investigated the RF wireless energy transmission as an alternative power source for wireless SHM sensor nodes [86, 87]. A layout of the RF power delivery system is given in **Error! Reference source not found.**. The average delivered power was estimated at 2.5 mW over a distance of 0.6 m with 1 W of X-band radiation. This experiment has shown that RF power delivery can be used to successfully operate the radio, which is the largest power consumer in a SHM sensor node [86].

As illustrated, wireless energy delivery has promise for providing power to the SHM sensor node or any other long-term wireless sensor nodes. For example, an unmanned aerial vehicle whose autopilot and GPS units are programmed to seek out specific coordinates populated by sensors can carry an RF source to activate each sensor. The sensor nodes that are powered by the RF energy will perform the intended measurement, analyze the data on a local computing embedded in the sensor node, and then send the results of the computation to the mobile host. The advantage of this transmission system is that power does not have to be embedded with the sensing system, but rather is transported to the node's vicinity and then wirelessly transmitted to the sensor node. It is anticipated that such a sensor network will have improved reliability and have inherent advantages when monitoring must be performed in locations that are physically difficult to access. Traditional energy harvesting systems at the node level could be coupled with the RF wireless energy transmission system to make more energy available for sensor nodes.

Power Conditioning and Storage

There is a signification amout of researc works into various types of power storage mediums and different circuits to maximize the electric power generated. A typical energy harvesting circuit is shown in **Error! Reference source not found.**. The AC signal generated by the energy harvesting medium is first rectified, then stored in a capacitor where it is subsequently used to charge the battery or any other energy storage medium. Some additional elements including DC-DC step down converters, voltage regulators, charge controllers, and charge pump circuits are employed to this circuit to maximize the power flow. All of the circuitry are designed so that the impedance of harvesting medium and charging circuit can be matched, a more consistent and efficient DC signal can be generated, and the efficient control of energy accumulation can be achieved.

Much of the research into energy harvesting has dealt with optimizing the power harvesting configuration or developing circuitry to store the energy. One such study was performed by Kasyap *et al*. [88], who used the concept that the energy transfer from the piezoelectric to the load is maximized when the impedance of the two are matched. The authors provide a description of the fly back converter circuit and the equations needed to set the circuit impedance to the desired value. Ottman *et al.* [89] and Hofmann *et al*. [90] studied the use of an adaptive step down DC-DC converter to maximize the power output from a piezoelectric device, which found that the power output could be increased by as much as 400%.

One common issue identified for energy harvesting devices is that the amount of energy generated by harvesting mediums is not sufficient to power most electronic devices. Thus, for energy harvesting technology to make its way into the commercial market, methods of accumulating and storing the harvested energy until a sufficient amount can be recovered to power the portable electronics are the key to a successful power harvesting system [28]. One of the first researchers to realize the need for power storage circuitry was Starner [91], who discussed the idea of using a capacitor and rechargeable battery for power harvesting with some advantages and disadvantages of each listed. This concept was taken a step farther by Kymissis *et al.* [32], who developed a piezoelectric system that would harvest the energy lost during walking and used it to power a radio transmitter. Their circuit used a capacitor as the storage medium, with the additional components to allow it to be charged to a desired level.

Because of the poor energy storage characteristics, the capacitors severely limited the number of applications for energy harvesting. Therefore, Sodano *et al*. [28] investigated the ability to use the energy from the piezoelectric material to recharge a discharged battery. Their study showed that a watch battery could be recharged from a completely discharged state in less than one hour by vibrations consistent in amplitude with those found on a typical vibrating machine. Guan and Liao [92] compared the performance of energy storage devices, including conventional capacitors, rechargeable batteries, and supercapacitors. They concluded that the supercapacitors are more attractive than rechargeable batteries because they have higher charge/discharge efficiency, higher adaptability and much longer lifespans. However, they also have a higher self-discharge rate.

For the RF transmission, the efficiency of the RF energy transfer method lies in the intelligent design of an efficient antenna along with a circuit capable of converting and amplifying low-amplitude, high-frequency AC signals to DC voltage. The rectification is a major source of energy loss in harvesting devices. In order to reduce the loss from the rectification diodes, a Schottky barrier diodes have been typically used. Compared to other energy generators, TEG does not require a means of rectification because the output of the TEG is a DC signal, which simplifies the associated electronic circuit design.

Applications to SHM

Although the energy harvesting techniques are still in a development stage, several conceptual designs for applications into SHM have been proposed. Elvin *et al*. [93] proposed a self-powered damage detection sensor using piezoelectric patches. A network of self-powered strain energy sensors were embedded inside a structure, and a moving cart capable of applying a time-varying dynamic load was driven over the structure. The harvesters convert this applied load into electricity and provide a power for sensors in order to measure the strain and to send the results to the moving cart, as shown in **Error! Reference source not found.**. James *et al*. [94] also proposed a prototype of self-powered system for condition monitoring applications. The devices, using a low-power accelerometer as a sensor, are powered by a vibration-based electromagnetic generator, which provides a constant power of 2.5 mW. However, the systems are not equipped with a local computing capability and only send out the direct sensor readings.

Discenzo *et al*. [95] developed a prototype self-powered sensor node that performs sensing, local processing and telemeters the result to a central node for pump condition monitoring applications, shown in **Error! Reference source not found.**. A wireless mote system was integrated with a piezoelectric energy harvesting technique. The device was mounted on an oil pump, and a cantilever piezoelectric beam tuned to the excitation frequency was embedded with the sensor node to extracted energy from the pump vibration. The maximum power output of 40 mW was achieved.

Pfeifer *et al*. [96] investigated the development of self-powered sensor tags that can be used to monitor the health of a structure. A microcontroller was powered by a piezoelectric patch (7.5 x 5 cm). Once powered, the microcontroller operates the sensor array, performs the local computing, and saves the results of computation into a RFID tag. By storing the data in non-volatile memory, the data can be retrieved by a mobile host, even if the sensor node does not have enough power to operate. In a laboratory setting, the piezoelectric harvester can deliver enough energy to the microcontroller for 17 seconds of operation. A schematic of this system is shown in **Error! Reference source not found.**.

Inman and Grisso [97] propose an integrated autonomous sensor node that contains the elements of energy harvesting from ambient vibration and temperature gradients, a battery charging circuit, local computing and memory, active sensors, and wireless transmission. These elements could be autonomous, self contained, and unobtrusive compared to the system being monitored.

Mascarenas *et al*. [98] experimentally investigated the RF wireless energy transmission as a power source for wireless SHM sensor nodes. They experimentally demonstrated that the delivered RF energy could be stored and used to successfully operate the radio, which is the largest power consumer in a SHM sensor node. Greve *et al*. [99] developed an inductively coupled Lamb wave transducer that eliminates the need for direct electrical connections. Signals were coupled into and out of the transducer using two probe coils, and the experiments show that return signals of millivolt amplitude are obtained when the transducer is excited with 10-V amplitude pulses.

Ha and Chang [100] assessed the suitability and efficiency of energy harvesting techniques for an SHM system based on the network of piezoelectric sensors and actuators. They concluded that total power requirement of the piezoelectric Lamb-wave based SHM far-exceeds the current energy harvesting capability. However, they suggested that the passive sensing system, which uses passive acoustic emission and detects an accidental impact event, would be a good candidate for energy harvesting technology because of the low power requirement and very low duty-cycle.

Energy harvesting is slowly coming into full view of the SHM and the more general sensing network communities. With continual advances in wireless sensor/actuator technology, improved signal processing technique, and the continued development of power efficient electronics, energy harvesting will continue to attract the attentions of researchers and field engineers. However, it should be emphasized that a tremendous research effort is still required to convert, optimize and accumulate the necessary amount of energy to power such electronics.

FUTURE RESEARCH NEEDS AND CHALLENGES

While it is noted that there is tremendous research into the development of energy harvesting schemes for large-scale alternative sources such as wind turbines and solar cells and that these large-scale systems have made the transition from research to commercial products, energy harvesting for embedded sensing systems is still in it infancy. Also, there is no clearly defined design process to develop such energy harvesting for embedded sensing systems. Therefore, in this section, outlines future research areas for energy harvesting will be outlined in order to transition the current state-of-the-art to full-scale deployment in the current practice of SHM and sensing networks.

As identified, the major limitations facing researchers in the field of energy harvesting revolve around the fact that the energy generated by harvesting devices is far too small to directly power most electronics. Therefore, the efficient and innovative methods of storing electric energy are the key technologies that will allow energy harvesting to become a source of power for electronics and wireless sensors. Several energy storage mediums, including rechargeable batteries, capacitors, or ultracapacitors should be carefully selected depending on a specific application. Another exciting possibility is the emerging technology of flexible, thin-film batteries or power-fiber batteries, that can be fully integrated into energy harvesting mediums, forming the concept of *structural batteries* or *harvesting batteries*. For instance, 5x5 cm patches consisting of 300 power-fibers are projected to store 25 mWh of energy [101]. It should also be emphasized that, when using any storage medium, the duty cycle of the application must be considered, as this factor drastically changes the design parameters and associated electronics. It is necessary to match the duty cycle to the time required to store enough energy until it is needed by electronics. It is also worthwhile pursuing a hybrid system that integrates energy harvesters with a RF wireless energy delivery system. The energy delivery system can be used to convey activity commands or it may provide additional energy if the harvester does not have enough energy to operate a sensor node.

Research on energy harvesting materials has focused mainly on determining the extent of power capable of being generated rather than investigating applications and uses of the harvested energy. The practical applications for energy harvesting systems, such as wireless self-powered SHM sensing networks, must be clearly identified with emphasis on power management issues. Application-specific, design-oriented approaches are needed to help with the practical use of these technologies. It is also suggested that the biggest roadblock for using energy harvesting devices is the lack of clear design guidelines that help determine how to characterize the ambient energy, what circuits and storage devices are best for a given application, and what strategies are best to integrate the harvesting devices into embedded sensor units. Developing such guideline demands substantial research efforts to define the key parameters and predictive models affecting efficient energy harvesting.

Reliability is an essential requirement for any energy sources. Because many vibration-based harvesters are designed to operate at their resonances, the systems will be inherently unstable after the long operation cycles. Also, any energy sources for field use should be able to withstand harsh environmental conditions. The reliability and robustness must be proved before the energy harvesting techniques can be used in practice.

Few studies addressed the integrated use of available energy harvesting devices. Each energy harvesting scheme needs to be compared precisely to the other methods and, if necessary, integrated together to maximize the energy generation under a given environmental condition. To realize this integration, a general standard should be established to address the technical capabilities of each energy source for system integrators so that they can easily assemble components for final design.

The goal of maximizing the amount of the harvested energy involves several factors, including electronics optimization, characterization of the available ambient energy, selection and configuration of energy harvesting materials, integration with storage mechanisms, along with the power-optimization and power-awareness design. Few studies have addressed these issues in an integrated manner from the multidisciplinary engineering perspective. Finally, it has been identified that, although several energy harvesting devices are developed and fabricated as a prototype, the performance of these techniques in real operational environments needs to be verified and validated.

CONCLUSION

This paper presents the state-of-the–art in energy harvesting as it has been applied to SHM embedded sensing systems. Various existing and emerging sensing modalities used for SHM and their respective power requirements were first summarized and a discussion of SHM sensor network paradigms, power requirements for these networks and power optimization strategies were discussed. Various approaches to energy harvesting and energy storage were then discussed and limitations associated with the current technology are addressed. This paper also addressed current energy harvesting applications and system integration issues, with a summary of applications to SHM sensing systems. This paper concludes by defining some future research directions and possible technology demonstrations that are aimed at transitioning the concept of energy harvesting for embedded SHM sensing systems from laboratory research to field-deployed engineering prototypes.

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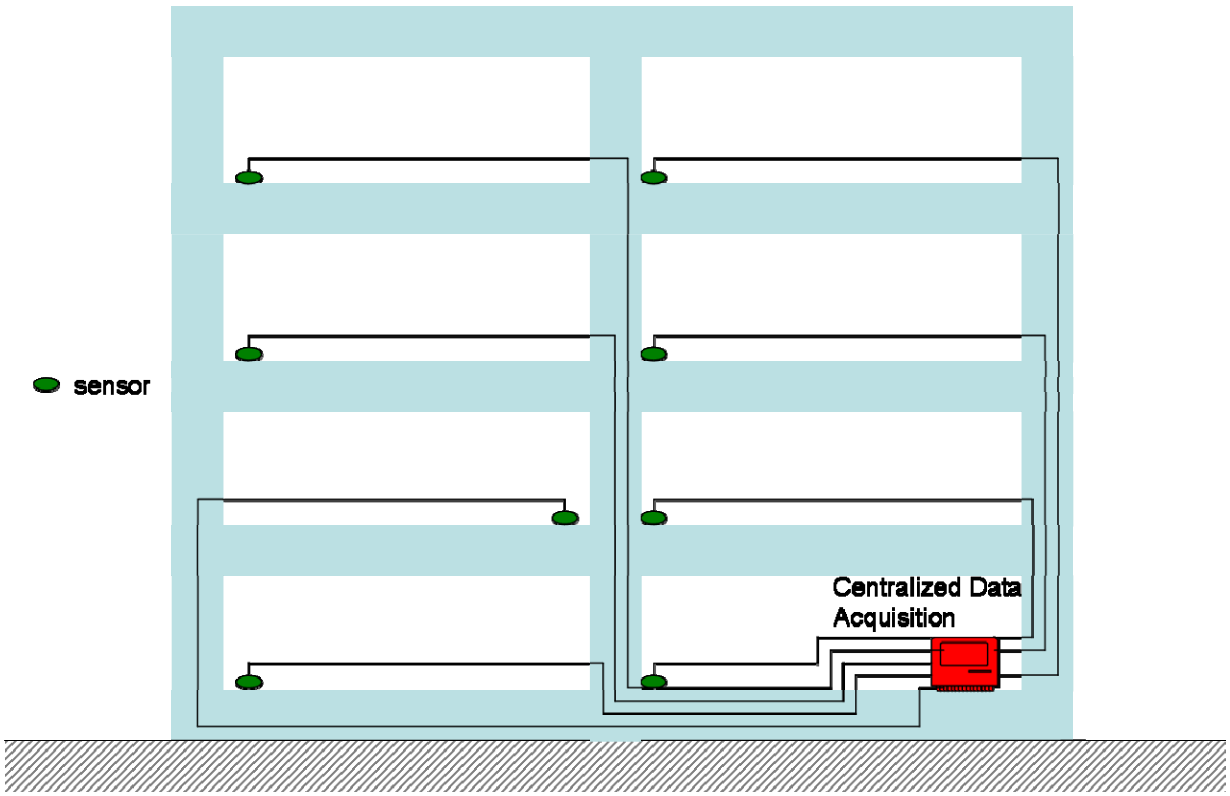

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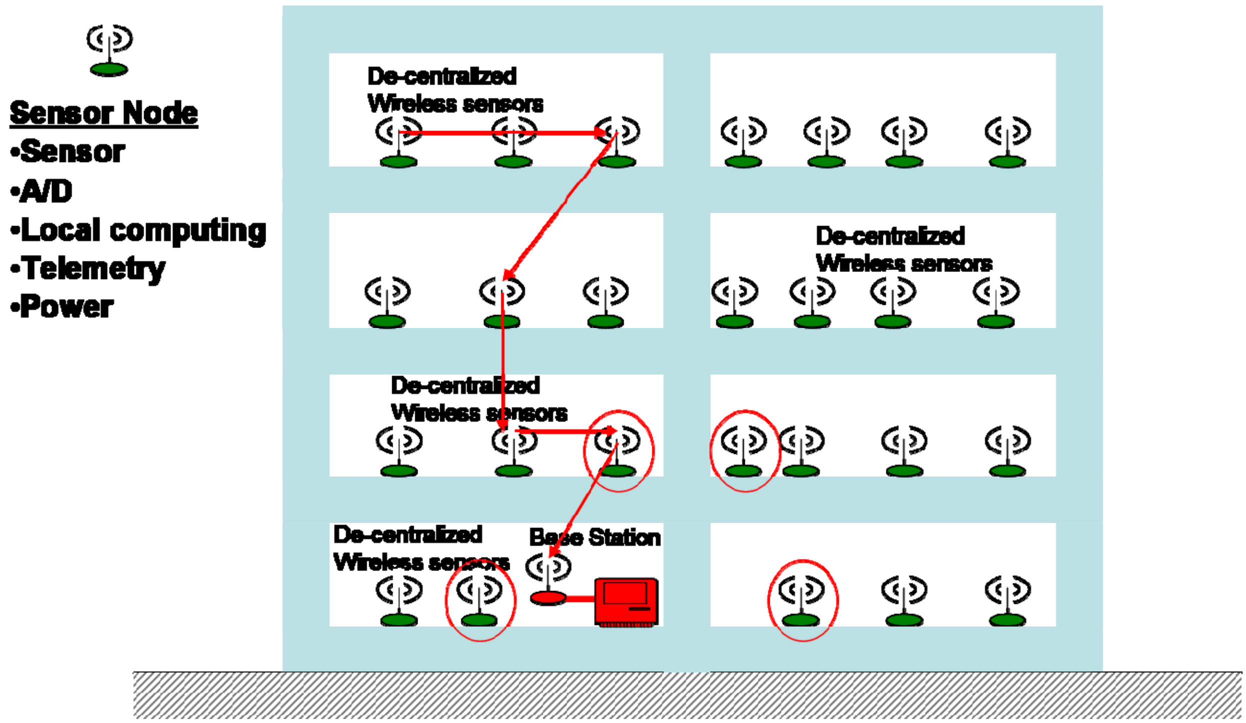

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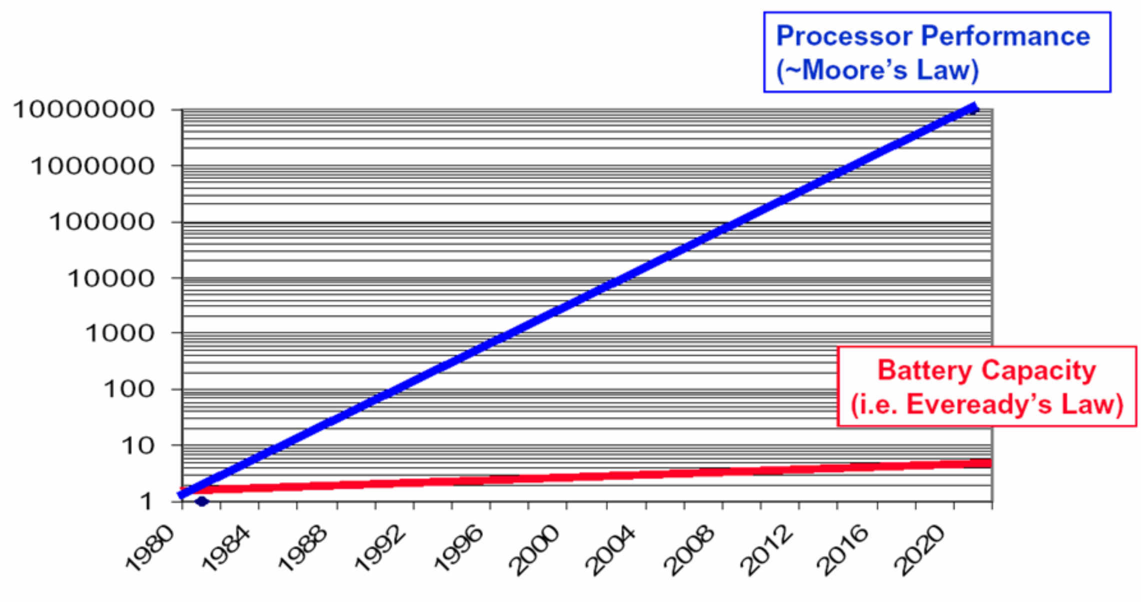

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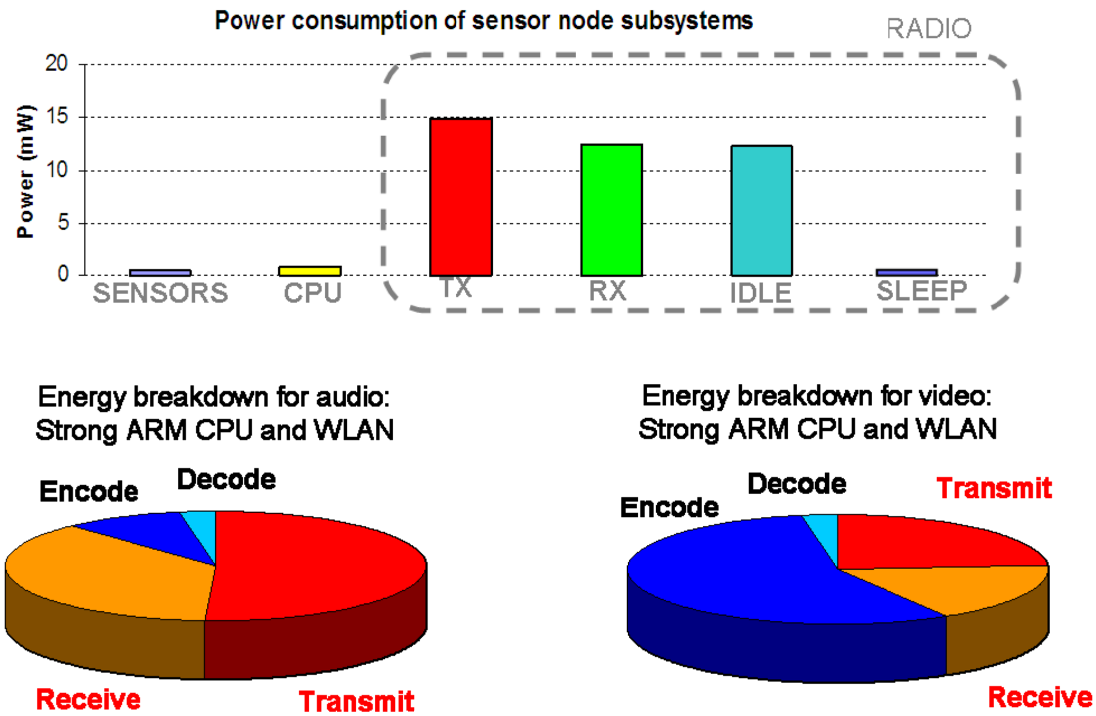

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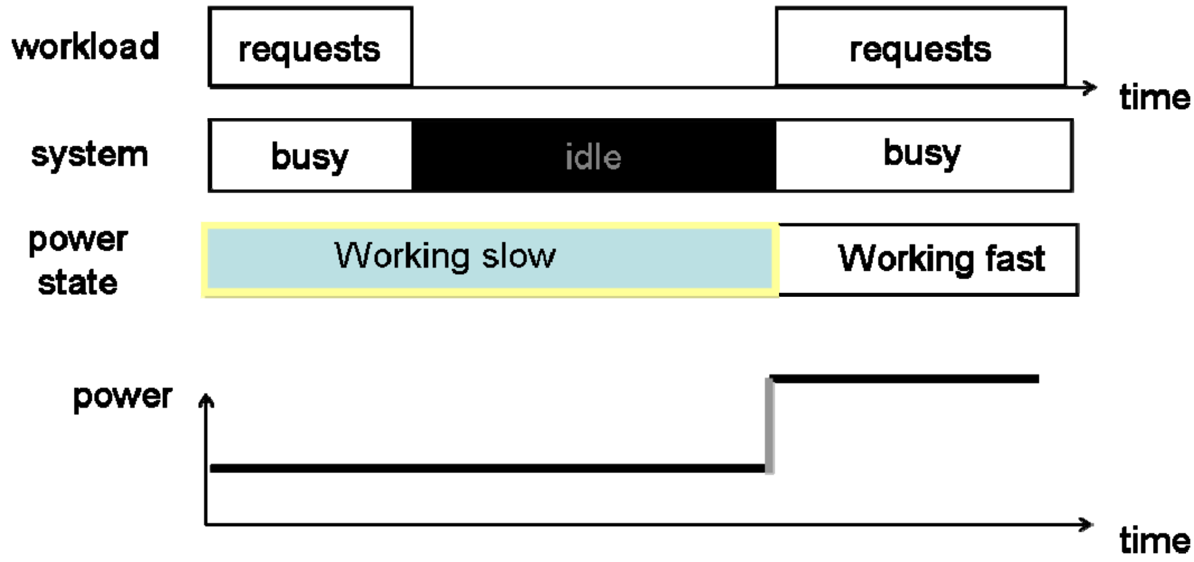

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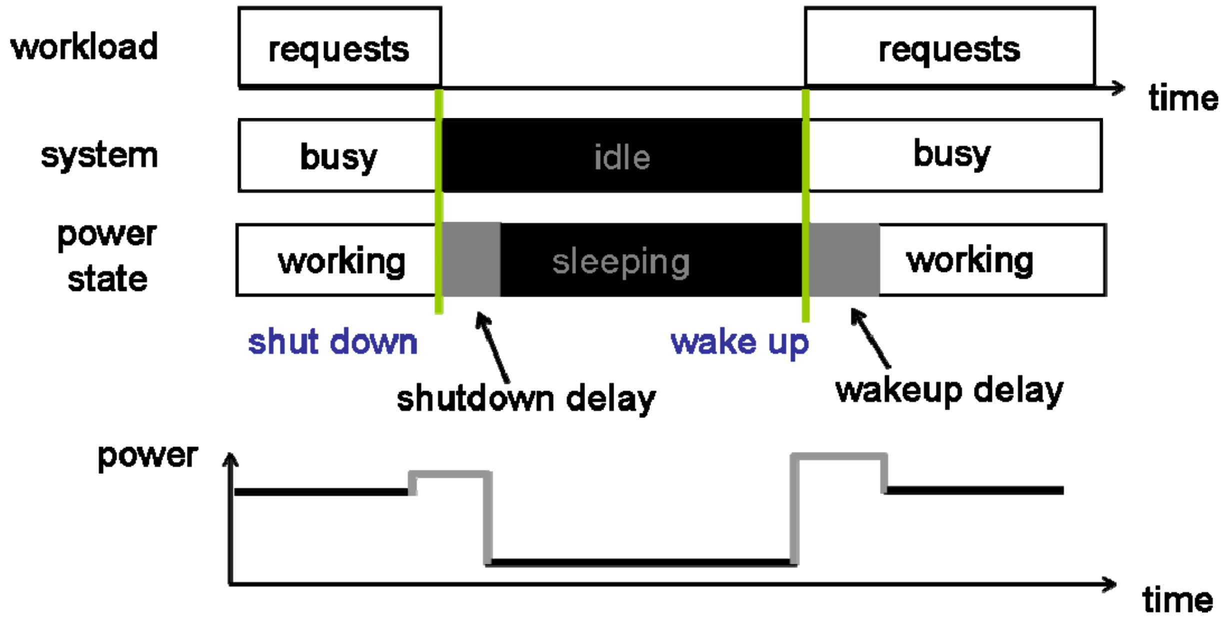

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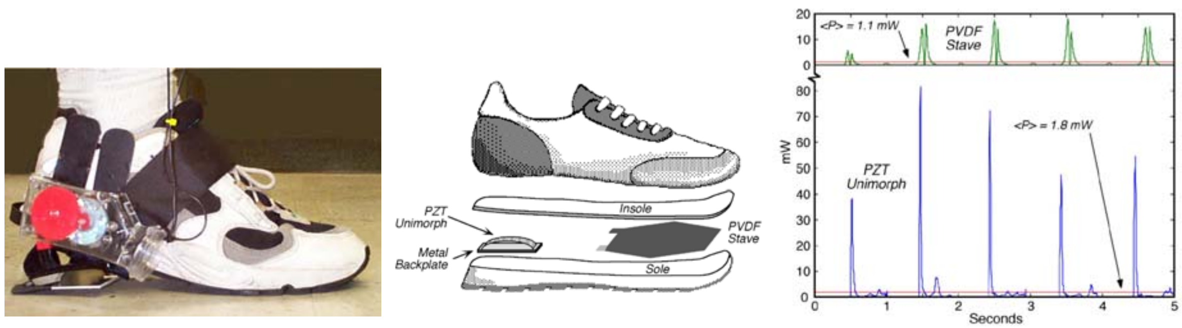

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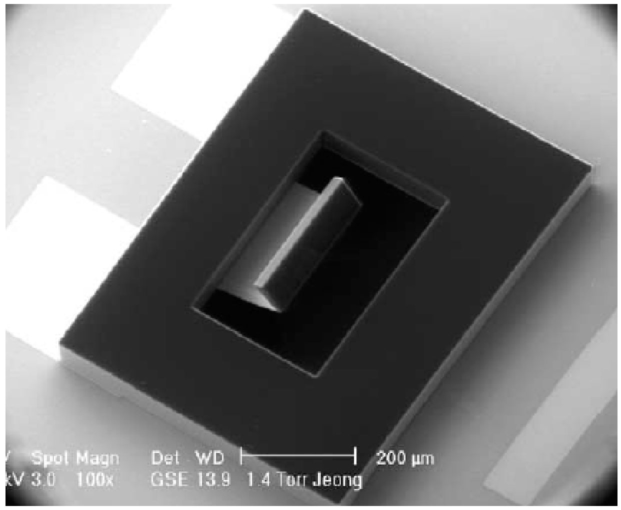

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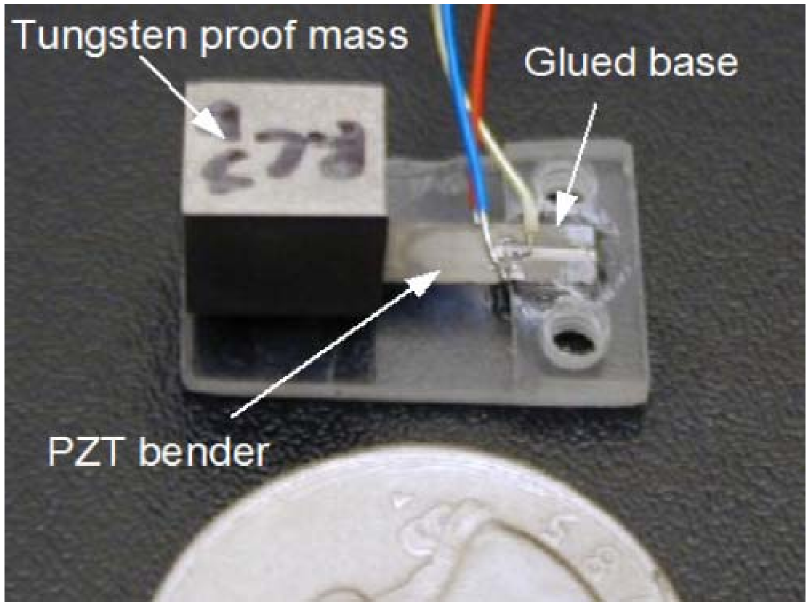

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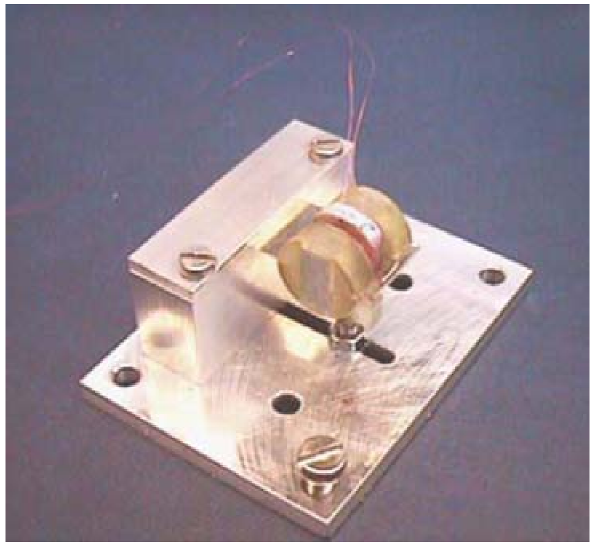

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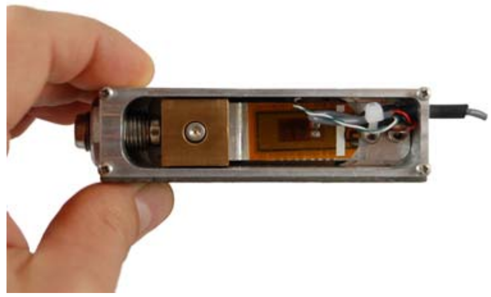

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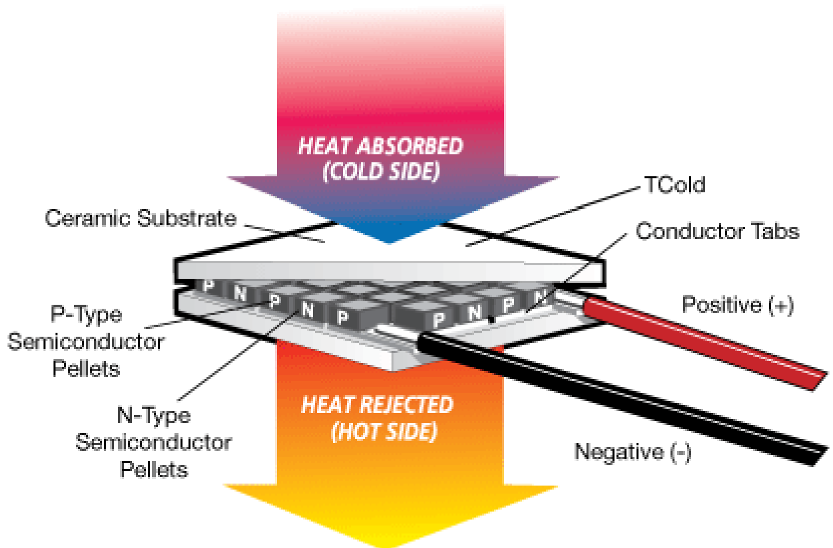

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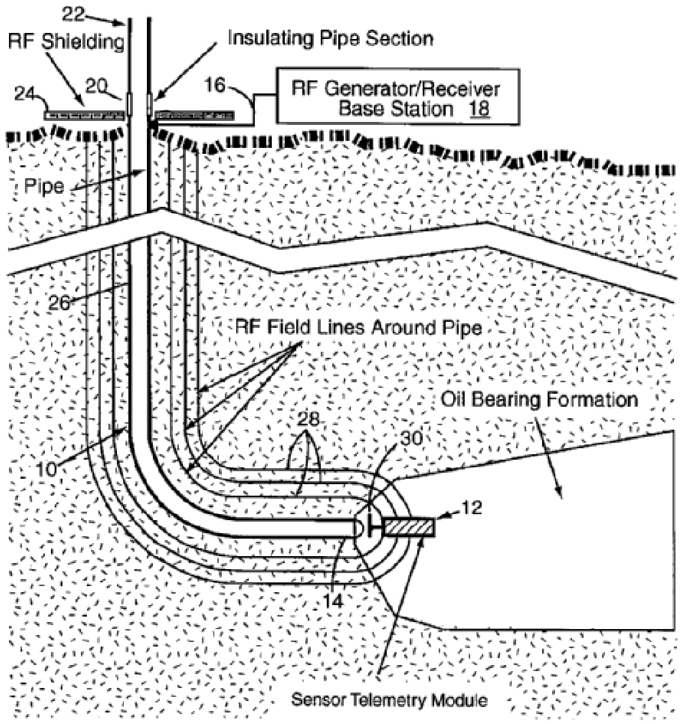

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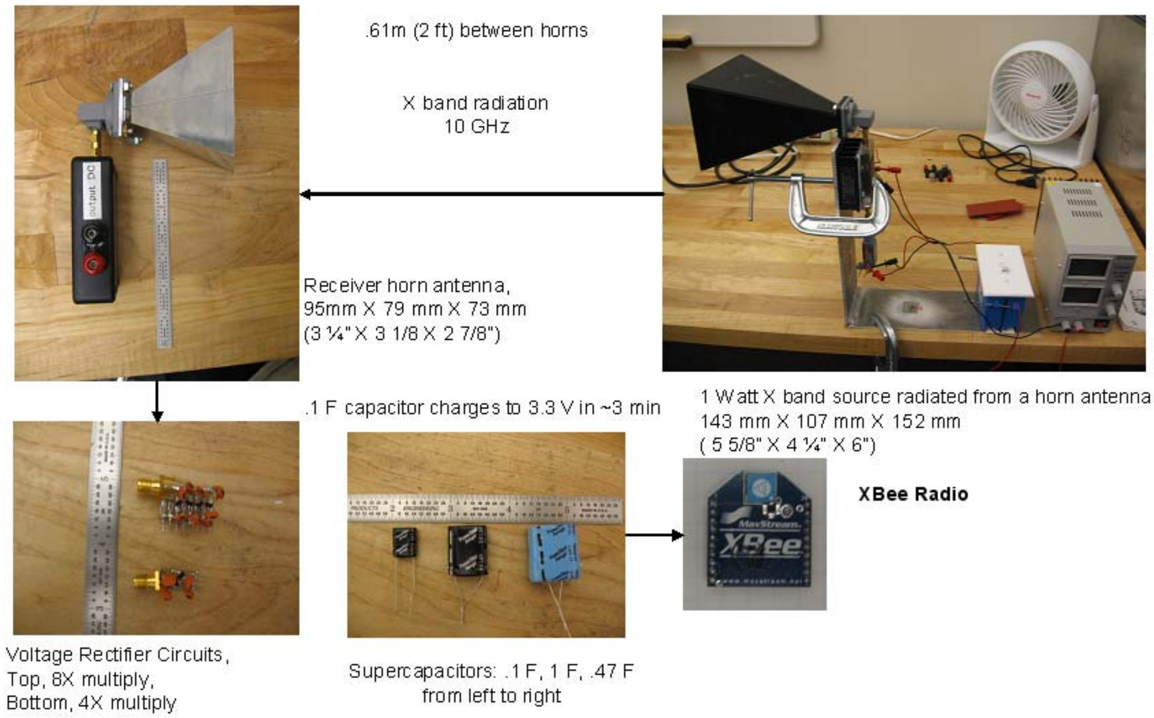

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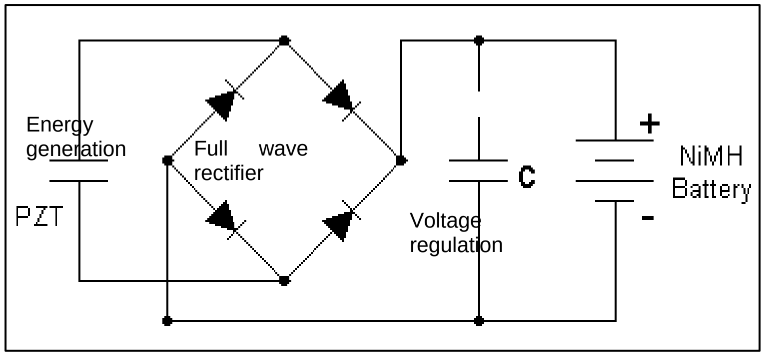

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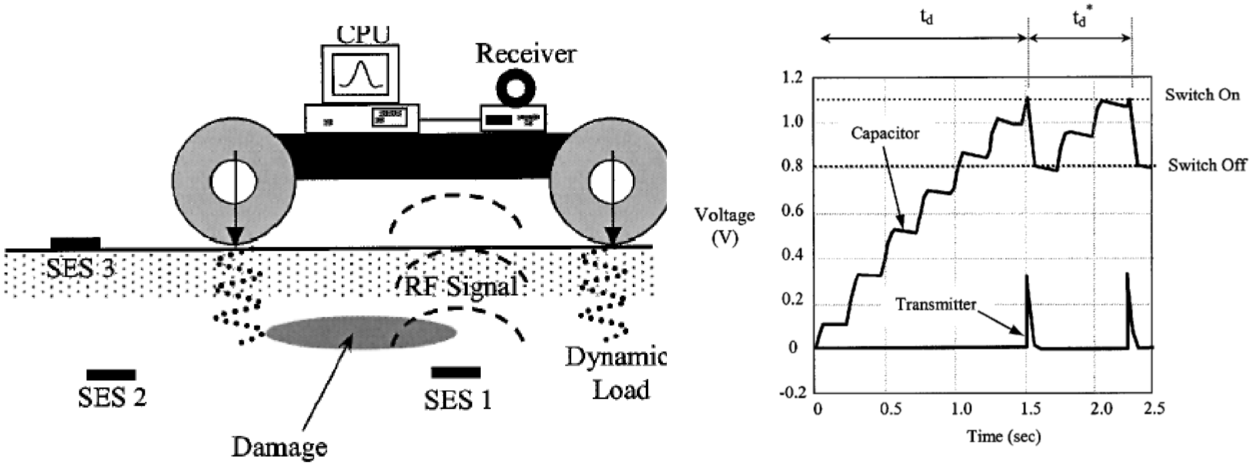

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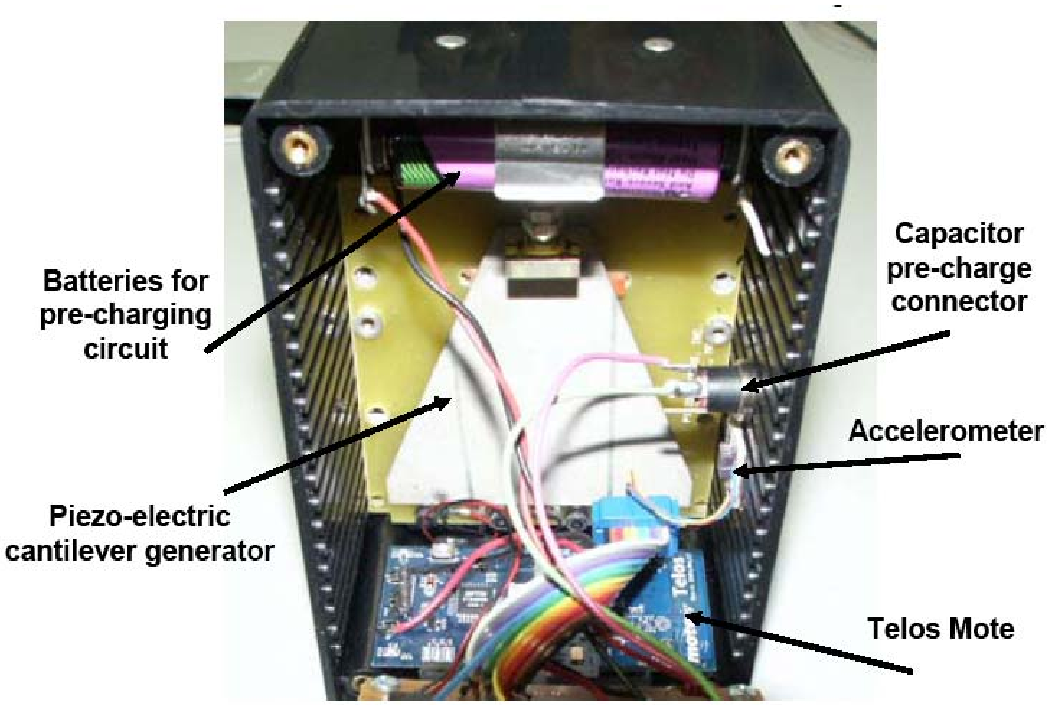

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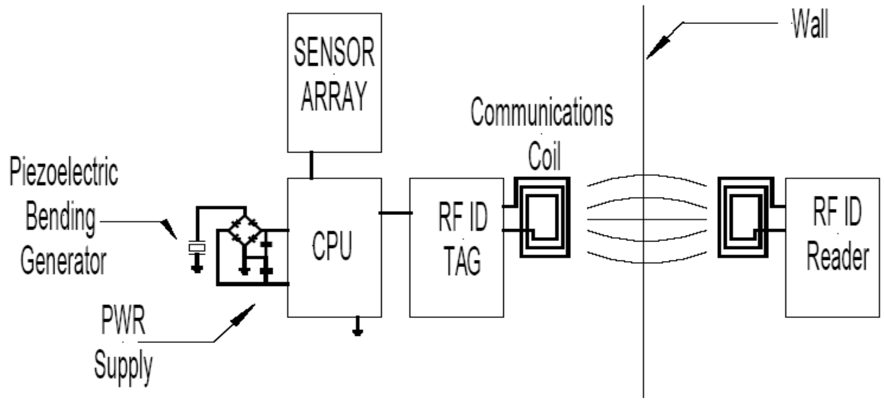

Figure 18. Diagram of self-powered sensor system. (Source: Pfeifer et al [96])

Table 4. Comparison of energy sources (Source: Roundy [26])

		Power Density (μW/cm^3) 1 Year Lifetime	Power Density (μW/cm^3) 10 Year Lifetime	Source of Information
Scavenged Power Sources	Solar (Outdoors)	15,000 – direct sun 150 – cloudy day	15,000 – direct sun 150 – cloudy day	Commonly Available
	Solar (Indoors)	6 – office desk	6 – office desk	Roundy [26]
	Vibrations	200	200	Roundy [26]
	Acoustic Noise	0.003@ 75 dB 0.96 @ 100 dB	0.003@ 75 dB 0.96 @ 100 dB	Theory
	Daily Temp. Variation	10	10	Theory
	Temperature Gradient	15 @ 10 ^{o}C gradient	15 @ 10 ^{o}C gradient	Roundy [26]
	Shoe Inserts	330	330	Starner 1996 [91]
Energy Reservoirs	Batteries (non-recharg. Lithium)	45	3.5	Commonly Available
	Batteries (rechargeable Lithium)	7	0	Commonly Available
	Fuel Cells (methanol)	280	28	Commonly Available
	Nuclear Isotopes (Uranium)	6x10^{6}	6x10^{5}	Commonly Available

Table 5. Energy harvesting demonstrated capabilities (Source: Paradiso and Starner [30])

Energy Source	Performance
Ambient radio frequency	< 1 μW/cm^2
Ambient light	100 mW/cm^2 (directed toward bright sun) 100 μW/cm^2 (illuminated office)
Thermoelectric	60 μW/cm^2
Vibrational microgenerators	4 μW/cm^3 (human motion – Hz) 800 μW/cm^3 (machines – kHz)
Ambient airflow	1 mW/cm^2
Push buttons	50 μJ/N
Hand generators	30 W/kg
Heel strike	7 W potentially available (1 cm deflection at 70 kg per 1 Hz walk)

Table 6. Comparison Elements between Electromagnetic and Piezoelectric Systems (Source:Poulin *et al*. [55])

System	Electromagnetic	Piezoelectric
Constraint	Low	High
Displacement	High	Low
Voltage	Adjustable	High
Current	Adjustable	Low
Resonant Frequency	Adjustable	High
Output impedance	Resistive	Capacitive
Adapted Load	Adjustable	High