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ENERGY HARVESTING METHODS FOR STRUCTURAL HEALTH MONITORING USING WIRELESS SENSORS: A REVIEW

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ABSTRACT

Structural Health Monitoring (SHM) implies monitoring the performance of structures using sensors to get an advance warning of the loss of structural capacity or potential collapse. Wireless-sensor based monitoring system is found to be advantageous over traditional wire-based system because of their ease of implementation and maintenance. However, power supply is an important concern for wireless sensors used in monitoring of civil engineering structures. While there are different efficient power usage methods and power supply solutions available for wireless sensors, their applications to SHM systems for civil infrastructure are not standardized. Energy harvesting by means of converting energy from the surrounding environment provides a desirable solution to address the issue of finite power source for wireless sensors. There are several sources of renewable energy that can be harnessed to generate electrical energy for the sensors. This paper reviews some of these energy harvesting sources and provides their working concept, brief idea about related research and a current state-of-art of their applications for structural health monitoring of civil engineering structures. Solar and mechanical energy harvesters have the most implemented applications for monitoring structures currently.

Keywords: Structural Health Monitoring, Wireless sensors, Energy harvesting

1. INTRODUCTION

Structural Health Monitoring (SHM) of civil engineering structures is essential as any structural failure leads to huge loss of life and property. Wireless sensing networks provide flexibility in application of SHM by reducing the cost, decreasing labour interference and providing assessment with high accuracy. However, power supply is a prime concern for wireless sensors. It is not practical to keep replacing or recharging their batteries. Some sensors are even located at inaccessible regions on structures like bridges, which make it impractical to use batteries as power source. Hence, an alternative source, energy harvesters are being used to power wireless sensors by harvesting other energy sources like sunlight, vibrations, wind etc. and converting them to electrical energy. Autonomous structural health monitoring is the need of the hour for monitoring a large infrastructure with several wireless sensor nodes and energy harvesting plays a major role to achieve it.

There has been a lot of research related to energy harvesting technologies and designs of energy harvesting generators (like Mateu and Moll 2005, Davidson and Mo 2014, etc). It is a mature technology and is too broad for the current paper. This paper provides a state-of-art review of available research on energy harvesting methods for application SHM of civil engineering structures. The energy sources considered for survey in this paper are solar, mechanical, thermal, radio frequency and hybrid energy sources.

2. WIRELESS SENSORS FOR STRUCTURAL HEALTH MONITORING

Structural health monitoring (SHM) aims at monitoring behaviour of structures to assess structural performance and evaluate structural damage. Civil infrastructure includes buildings, bridges, tunnels, dams, etc. They are designed to resist static and dynamic loads like gravity, traffic, snow, wind and earthquake. For accurate structural assessment, it is necessary to effectively capture varied structural responses under different excitation and ambient scenarios. SHM can be wired or wireless depending on the mode of transfer of the acquired structural data by sensors collecting structural response at critical locations. Wired SHM has several disadvantages like high cost, labour-intensive installation, high susceptibility to disturbance due to human or environmental causes and inflexibility of sensor system modifications (Zhou and Yi 2013). These issues can be addressed by wireless sensor network (WSN) as they are easily deployable and serve as a practical low-cost solution (Chintalapudi et al. 2006). WSN comprises wireless sensors, which are autonomous data acquisition nodes to which traditional structural sensors (e.g. strain gages, accelerometers, linear voltage displacement transducers, inclinometers, among others) can be attached. Each sensor has following sub-systems: sensing interface, computational core, wireless transceiver and, for some, an actuation interface (Lynch and Loh 2006). For functioning of all these sub-systems to maintain desirable connectivity in the WSN, a power source providing energy is essential.

3. POWER SUPPLY TO WIRELESS SENSORS

There are several design considerations for SHM using WSN which include suitable network topology with multi-hop configuration for full coverage, high-resolution sensors with optimal sampling rates, good processing capabilities in sensors, high speed and reliable communication, and effective time synchronization to name a few. Structures are designed to serve for many years and the sensor network is expected to function throughout their lifetime. A wireless sensor turns inactive and useless when the power supply is disrupted and it fails to contribute to the utility of the network as a group (Kausar et al. 2014). Hence, lifetime of sensors is directly related to their power source and battery life. Batteries are a common power source for wireless sensor nodes but they eventually degrade and have to be recharged or replaced. This is cumbersome and sometimes impractical due to placement of sensors in inaccessible locations. Thus, batteries provide a limited lifetime to the sensor nodes and network. There are several energy efficient methods for slow degradation of available power. As summarized by (Sudevalayam and Kulkarni 2011), enhancement of longevity some of the battery-powered sensor nodes are achieved through energy-aware MAC protocols (SMAC, BMAC, XMAC), power aware storage, routing and data dissemination protocols, duty-cycling strategies, adaptive sensing rate, tiered system architectures, and redundant placement of nodes. These methods minimise the battery power usage but still, the battery lifetime is limited. Theoretically, unconstrained power can be supplied by energy harvesting methods. The energy harnessed can be stored in rechargeable batteries and super-capacitors. NiMH and Li-based batteries are most viable for energy harvesting nodes. Super-capacitors also store power but it is suitable for cases when ample energy is available as they have high self-discharge rates. Super-capacitors have infinite recharge cycles theoretically and do not suffer from memory effect. They can be used solely or as buffer to stabilise jittery energy source supply to batteries (Jiang et al. 2005), (Sudevalayam and Kulkarni 2011). This article reviews the current state-of-art of research in energy-harvesting methods for wireless sensors for applications in SHM of civil engineering structures.

4. ENERGY HARVESTING METHODS FOR SHM AND THEIR RECENT ADVANCEMENTS

The term energy harvesting means the process of energy extraction from the environment or from a surrounding system and its conversion to useable electrical energy (Park et al. 2008). The energy can be captured from ambient sources as well as other generated energy sources. Figure 1 illustrates the scheme for providing power to wireless sensor nodes by energy harvesting.

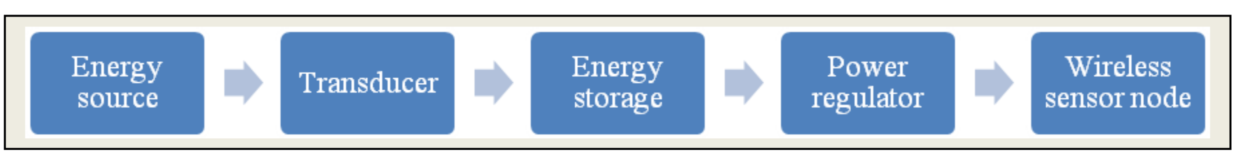

Figure 1: Energy harvesting application for powering wireless sensor node

The energy sources reviewed in this paper are solar, mechanical, thermal, radio frequency and hybrid energy sources. A brief comparison of power densities of these energy harvesting sources surveyed by (Roundy 2003) is shown in Table 1.

Table 1: Comparison of energy harvesting methods

Energy source	Power Density (μW/cm3)	Evaluation
Direct solar energy (outdoors)	15000	Excellent performance on sunny days making it a good option for sensors deployed outdoors.
Solar energy at office desk (indoors)	6	Very low energy produced.
Vibrations inside buildings	200	Sufficient power generation for monitoring buildings.
Daily temperature variation	10 approximately	Insufficient power generation.
Temperature gradient	15 @ 10 ºC gradient	Promising technology but is rare in nature.
Passive human power by shoe inserts	330	Good conversion efficiency but transferring electricity from shoe to wireless sensor networks is a challenge.

5. SOLAR ENERGY HARVESTING

Photovoltaic or solar cells harvest electrical energy from light energy, which is already an established technology. Table 1 (Sudevalayam and Kulkarni 2011), (Jiang et al. 2005) and with contributions from Raghunathan et al. 2005, Park and Chou 2006, Simjee and Chou 2006, Corke et al. 2007, Minami et al. 2005 summarizes some features of popular solar energy harvesting sensor nodes. For solar energy harvesting, outdoor applications are preferred due to high solar energy availability in outdoor conditions, and could be very useful for SHM of outdoor infrastructure like roads and bridges. Solar energy is not available all the time though; so a design using harvest-store-use architecture is the most practical option (Sudevalayam and Kulkarni 2011). Since structures are designed for a long lifetime, sensors too should be operational for a long time. Thus, for SHM purposes, nodes with solely super-capacitor type of energy storage should be used as batteries will eventually need replacement, while supercapacitors do not. (Miller and Spencer 2009) have developed and validated solar powered IMote2 wireless smart sensor system for monitoring a cable stayed bridge, Jindo Bridge in South Korea. (Jang et al. 2010) have validated the successful deployment of this system. (Musiani et al. 2007) created SHiMmer which is a solar energy harvesting system for sensing and actuating civil engineering structures. It uses super-capacitors for energy storage and low power consuming micro controller and radio. (Chae 2012) developed and tested 45 solar powered sensors on Yongjong Grand Bridge. (Hassan et al. 2012) have proposed and tested a wireless sensor system powered by harvested solar energy for monitoring cracks in concrete structures. (Inamdar 2012) designed a photovoltaic system to monitor strains in bridges. (Kurata et al. 2011) created and installed solar powered autonomous wireless monitoring network using Narada sensing unit (Zimmerman and Lynch 2009) on New Carquinez Suspension Bridge in California. (Ho et al. 2012) developed a solar powered autonomous smart wireless sensor system and validated it on cable-stayed Hwamyung Bridge in Korea. Microstrain has installed solar powered wireless sensors for structural health monitoring. (Arms et al. 2008). This system monitors strain, temperature and vibrations of the Goldstar bridge. Microstrain also has installed solar energy powered system for monitoring Great Road State Bridge in North Smithfield (Nordbloom and Galbreath 2012). The current challenges with regard to solar energy harvesting are to estimate its availability and design the harvesting nodes according to the parameters of periodicity and magnitude of solar energy. The energy harnessed is not at a constant voltage, and the generated energy is proportional to the surface area of the solar panel. New materials like black silicon with high efficiency is being developed to improve the efficiency of these systems. Also, hybrid energy harvesting methods are becoming popular. (Sudevalayam and Kulkarni 2011), (Stojcev et al. 2009).

Table 2: Features of solar energy harvesting nodes

Node	Storage type with capacity	Sensor node used	Energy harvesting features
Heliomote	Ni-MH Battery (1800 mAh)	Mica2	Harvesting-aware microcontroller operation.
Hydrowatch	Ni-MH Battery (2500 mAh)	TelosB	Simple circuit design for low power generation and has been used for climate monitoring purposes.
Fleckl	Ni-MH Battery (2500 mAh)	NA	High power generation for long durations by DC-DC regulator
Everlast	Supercapacitor (100F)	NA	Efficient charging of super-capacitor by Pulse Frequency Modulated (PFM) regulator with 20 years estimated lifetime.
Solar Biscuit	Supercapacitor (1F)	NA	Ineffecient communication protocol and needs improvement.
Sunflower	Supercapacitor (0.2F)	NA	Overall small in size with power adaptation facilities and switch regulator for efficient charging.
Prometheus	Supercapacitor (two 22F) & Li-poly Battery (200 mAh)	Telos	Complex charging circuit programmed by TinyOS leading to longer lifetime.
AmbiMax	Supercapacitor (two 22F) & Li-poly Battery (200 mAh)	Telos	Harvests both wind and solar energy

6. MECHANICAL ENERGY HARVESTING

Electrical energy can be obtained from energy generated when a device is subjected to some movement. This harvested energy can be converted to electrical energy by piezoelectric, electrostatic and electromagnetic conversions (Stojcev et al. 2009). This paper discusses piezoelectric and electromagnetic harvesting. Market survey of vibration based energy harvesting products was conducted by (Moghe et al. 2009) and it can be inferred that piezoelectric harvesters generate more power than inductive harvesters but at a higher frequency range.

6.1 Piezoelectric

Piezoelectric transducers can couple electrical and mechanical energy. Piezo-electric films like PVDF (Piezo-polymer Polyvinylidene Fluoride) and piezo-electric ceramic like PZT (Piezo-ceramic lead Zirconate Titanate) are two kinds of piezoelectric materials used for electrical energy generation on application of mechanical force on them. PZT is less flexible than PVDF as PZT is a ceramic (Sudevalayam and Kulkarni 2011). Still, PZT is more commonly used due to its ease of manufacturing leading to low cost and high electromechanical coupling constants. PVDF is a better choice under cyclic loads as PZT might develop fatigue cracks in such cases (Zhou et al. 2014). Literature reviews on piezoelectric transducers using vibration-based energy harvesting have been studied by many researchers like Sodano et al. 2004, Dutoit et al. 2005, Park et al. 2008, Gilbert and Balouchi 2008, Khaligh et al. 2010 and Kim et al. 2010. Vibration based energy harvesters are still in their infancy. In 1998, Kymissis et al. built shoe powered RF tag system powered by walking. While there are several other examples, this paper focuses on applications for structural health monitoring of civil engineering structures. (Wischke et al. 2011) designed piezoelectric harvester from vibrations of railways ties to sufficiently power the wireless sensor nodes. (Peigney and Siegert 2013) developed a device to generate power from traffic on highway with a piezoelectric cantilever bimorph consisting of a tip mass and two piezoelectric patches attached to the clamped end of a steel plate. (Xiang et al. 2013) performed theoretical analysis of piezoelectric energy harvesting from traffic passing on pavements. Results demonstrate increase in output power with increase in velocity of passing vehicles. (Kaur and Bhalla 2015) have conducted experiments and investigated energy harvesting from PZT patches in steel and reinforced concrete beams. (Cahill et al. 2014) experimentally validated use of PVDF based piezoelectric energy harvesters and an energy harvesting circuit for damage detection in reinforced concrete beam. (Erturk 2011) analysed moving loads for energy harvesting. (Xie et al. 2015) introduced a novel PZT piezoelectric harvester design containing two groups of series piezoelectric generators connected by a shared shaft which is driven by a linking rod attached with a hinge to a proof mass on the tip of a cantilever fixed on the roof to harness energy from a high rise building, and can act like a tuned mass damper to dissipate energy. Piezoelectric harvesters have the advantage of direct generation of voltage, but they also allow charge leakage sometimes (Stojcev et al. 2009). Typical highway bridges have low frequency excitation. Piezoelectric harvesters require vibrations in at least close to 100s of Hz. Hence, they are not in a mature state of technology for powering monitoring on bridges currently (Roundy 2003), (Sazonov et al. 2009), (Sodano et al. 2004).

6.2 Electromagnetic induction

Electromagnetic induction is the process of generating voltage due to varying magnetic flux around the conductor by movement of the magnet (Park et al. 2008). Ceramic, Alnico, SmCo, and NdFeB are the most common magnets and NdFeB is mostly used due to its properties of large magnetic field intensity, high coercive force and no issue of demagnetization due to generator vibration (Zhou et al. 2014). Several researchers have studied, analyzed and worked on improving the electromagnetic harvesters design and mechanism like Glynne-Jones et al. 2004, Stephen 2006, Poulin et al. 2004, Roundy 2005, El-Hami et al. 2001 and many others. (Jung et al. 2012) experimentally validated application of an electromagnetic harvesting device working on wake-galloping phenomenon of wind at a bridge site. Results showed that from a wind speed of 2.5–4.5 m/ s – 1, an average power of 50–370 mW can be generated. (Jung et al. 2012) developed a new electromagnetic harvesting device with a combination of moving mass with a rigid bar and motor attached to a gear part. (Kim et al. 2013) replaced the electromagnetic induction part with a moving mass and a rotational generator. This innovated design tuned the natural frequency of the structure by changing proof mass position. (Sazonov et al. 2009) developed a linear electromagnetic energy harvesting system and deployed it for powering wireless sensors on a rural highway bridge, RT Bridge in Potsdam, NY with low traffic volume. (Galchev et al. 2011) developed a parametric frequency-increased generator (PFIG) for enhancing low acceleration (0.1–0.5 m s−2), low frequency (2–30 Hz) and adjusting non-periodic vibrations on bridges. University of South Hampton's company Perpetuum developed electromagnetic energy harvesters for rail monitoring (Perpetuum 2013). (Wang and Yuan 2008) have developed magnetostrictive harvester, It has a high conversion efficiency and the maximum output power can reach 200 μW at a low frequency of 58 Hz (Davidson and Mo 2014). Electromagnetic harvesters show great potential for scaling to lower frequencies of bridge vibration (Sazonov et al. 2009). However, they are bulky in size for MEMs integration and further research also focuses on achieving resonance.

7. RF ENERGY HARVESTING

Another category of energy supply is wireless energy transfer where power generation is somewhere else and supplied wirelessly by electromagnetic wave or electromagnetic radiation. Transmission of microwave waves have been studied a lot in the past. RF transmission to low power devices is a new area (Taylor et al. 2009). Researchers like Strassner and Chang 2003, Ali et al. 2005, Ren and Chang 2006, Kim et al. 2006 and several others focus on designing antennas and rectennas, improving conversion efficiency and maximize output power (Park et al. 2008). (Mascarenas 2006) used wireless RF to supply electrical energy to SHM sensor node based on the piezoelectric impedance method by charging the capacitor. The central server was a controlled helicopter which could fly to the sensor nodes and exchange energy and data. The results showed charging of 0.1 F super-capacitor to 3.3 V in 200 seconds and the average power which can be delivered was calculated as 2.5 mW. This was the first attempt to wireless energy transfer to miniaturized wireless SHM sensor node (Mascarenas et al. 2007). (Farinholt et al. 2009) used RF energy transmission in Alamosa Canyon Bridge in New Mexico to charge a 0.1F super-capacitor to 2.4 V with transmission ranges of 1 to 2 metres. (Thomson et al. 2009) designed RF resonant cavity sensors interrogated by gated RF signals with possible strain resolution of less than 10 ppm at 8 m range, and displacement resolution of less than 0.01 mm at 4.5 m range. They suggest its applications for wireless sensors in civil infrastructure monitoring. RF transmission still needs further development. In RF transmission, there is attenuation of the wave during its travel (Taylor et al. 2009). Hybrid energy resources with RF delivery system are also a trending research area (Park et al. 2008).

8. THERMAL ENERGY

Seebeck effect is generation of electricity at the junction of two dissimilar metals with temperature difference (Park et al. 2008). Thermoelectric generators (TEG) work on this principle. TEG is constructed by arranging p-type and n-type junctions thermally in parallel and electrically in series. TEGs have an advantage over vibration energy harvesters as they do not operate on moving parts. But TEGs have the disadvantage of low efficiency with small thermal gradient and not easy to integrate with MEMs (Park et al. 2008). Investigations about TEGs have been carried out by many researchers like Lawreence and Snyder 2002, Rowe et al. 1997, Fleming et al. 2004 to name a few. Damaschke in 1997, developed a self starting TEG which operates at low input voltages i.e. below 300 mV using low-grade exhaust heat operating at temperature difference of 20 °C and less. In 2010, Lu and Yang 2010 presented a thermoelectric generator prototype which extracts heat energy from a radiator and powers the radio. (Sodano et al. 2007) investigated a Seebeck heat pump which uses solar radiation and waste heat to generate electricity in a passive configuration. Thermal electricity generation variables have been studied by Meydbray et al. in 2005 for low temperature gradient. (Abbaspour 2010) demonstrated how heat flow and temperature difference between inside and outside of buildings which is waste energy can be harvested to power wireless sensor nodes. (Inman and Grisso 2006) developed a system to carry out structural health monitoring of a panel using ambient vibrational and thermal energy. TEGs have been commercialized and have more application in structural health monitoring or powering automobiles, aircrafts and spaceships (Penella and Gasulla 2007, Thermogen 2015). However, there are not many applications developed for monitoring of civil infrastructure. Until recently the dimensions and weight of the devices were too large to integrate them with MEMS for monitoring purposes by wireless sensors.

9. HYBRID ENERGY SOURCES

A common suggestion listed by researchers in the field of energy harvesting is the combined use of several energy harvesting sources in the same devices to compensate and enhance each other and maximize the output. The first work in this regard was when in 2009, Xu et al. developed a nanogenerater which harnessed solar energy and mechanical energy simultaneously as well as independently showing enhancement of performance. In 2009, Wischke developed a hybrid energy harvester with piezoelectric and electromagnetic transducer. AmbiMax, developed by (Park and Chou 2006) can simultaneously harvest multiple energy sources to power wireless sensors. Magno et al. developed a platform for ultra low power continuous operation using solar and wind energy harvesters in 2014. (Farinholt et al. 2010) investigated use of piezoelectric bimorph cantilevers and TEGs for harvesting ambient vibrations and thermal gradients, respectively, from the Omega Bridge in Los Alamos, New Mexico.

10. CONCLUSION

Energy harvesting technology is a viable and long-term solution for power issues of wireless sensors. Autonomous independent sensor nodes can be created using energy harvesting mechanisms removing the constraint of continuous energy supply. Some common focus areas are improving the efficiency of harvesters, maximising the power output, better designs for low power micro-electronics, power generation model predictions. The summary of this paper is presented in Table 3.

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Table 3: Overview of energy harvesting systems for SHM applications

Energy harvesting system	Advantages	Limitations	SHM application for civil engineering structures state-of-art	Suitable deployment for maximum output
SOLAR	Mature technology, high power density for outdoors and easy to install.	Not periodic and not available 24 hours.	There are several applications in SHM, mostly in outdoor and need ample sunlight.	Outdoor structures like bridges, building and near the equator.
PIEZO-ELECTRIC	Direct generation of desired voltage and easy integration with MEMs.	Variation in properties with age, stress, temperature and leakage in charge.	Need high frequency vibration. Civil engineering structures have lower frequency, need amplifiers, they can be put into use. Most work for SHM applications is in lab stage.	Bridges with preferably heavy passing traffic, impulse loads from railways, buildings with vibration from ducts or machinery and cantilevered structures can generate energy with higher vibrations and piezoceramic patches.
ELECTRO-MAGNETIC	High reliability and no mechanical damping	Difficult to integrate with MEMs, low output voltage	There has been substantial amount of work using electromagnetic generators on bridges and it is promising.	Traffic induced bridges and railways.
RF	No of embedded storage and can supply power to remote areas.	Noise and loss of signals.	It has a lot of potential in SHM for civil infrastructure. Not much wireless energy transfer has been done in the past.	Structures in urban areas with dense communication installations where RF signals are easily available.
THERMAL	Low maintenance and high reliability	High cost with low conversion efficiency	Not much work yet for structural assessment as low thermal gradient leads to low efficiency.	It can be used in buildings due to their environment inside and outside.

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