



Energy Harvesting and Remote Sensor Networks, a Perfect Marriage

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But what can be done with such a low amount of power? Will I be able to power my cell phone? Not likely, however, micro-energy harvesters are ideally suited to supplying small amounts of power to sensor networks in hard to access environments or even in the human body.

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WHITE PAPER

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We are surrounded by batteries. They are in our toys, our cell phones, our garage door openers, remote controls, pace makers, etc. They take up space, they need to be replaced, and they are a waste disposal problem. Energy from the environment is available in many cases, but it is not in usable form, i.e. as electrical energy. "Micro-energy harvesting," which is designed to provide micro-watts of power, is an exciting area of research interest with potential in many electronic applications. The goal of micro-energy harvesting research and development is the elimination of batteries by converting available ambient energy (vibration, heat, wind, etc.) into usable electrical energy.

But what can be done with such a low amount of power? Will I be able to power my cell phone? Not likely, however, micro-energy harvesters are ideally suited to supplying small amounts of power to sensor networks in hard to access environments or even in the human body. For such applications, these sensor networks will change our lives for the better.

Current Problems Amenable to a Sensor Network Solution

Safety from Unauthorized Intruders

Imagine an array of hundreds of thousands of tiny sensors the size of a pea scattered over a large geographical area, all connected together sending their signals to a satellite. They might be dropped from an airplane like confetti. By subsequent remote programming each sensor would know its own location. Any one setting foot into the region would be sensed and located by the vibrations of their footsteps. Other visual sensors in a sparse array would identify the individual and communicate at a higher level to master controllers. Authorized people who belong within the sensor zone would be monitored with wearable transponders.

Safety on the Highway

What if the highways we drive on every day had an array of low cost self-powered vibration sensors? They would report traffic conditions through vibration. They would be able to monitor traffic patterns and even accidents; this information could be supplied to other drivers or emergency services for rapid response.

Bridge Safety

Several years ago, a bridge on the New York State Thruway unexpectedly collapsed. Several people died as the road they were driving on suddenly disappeared into a ravine. Imagine a sensor network composed of tiny battery-less strain sensors bonded to critical points on a bridge. They would remain permanently bonded to the bridge for many, many years. There would be no batteries to maintain. They could be monitored continuously from a master solar powered unit close to the bridge, or they could be periodically monitored from a mobile department of transportation vehicle in a single pass-by. At the first sign of excessive strain, the bridge could be examined and repaired.

Agricultural Monitoring

Today, high-end agricultural crops such as grapes are being monitored with sensor networks. Current systems use a small number of very large sensors units scattered throughout a vineyard to monitor sunlight, temperature, and humidity. Because of the current technology (ZigBee, see below), the sensor units must be battery powered. The sensor units report critical growing conditions within the field. By knowing the ambient conditions throughout a field, growers can optimize the amount of water, herbicide, pesticide, and fertilizer given to the vines. Rather than treating the entire field for disease, a local area can be treated, thus minimizing the amount of pesticide used. In the future, as costs come down, systems using energy harvesting and micro-electronic sensor technology will be deployed extensively in agriculture and for an ever larger number of crops.

Safety in the Air

Imagine an airplane with a thousand tiny stress sensors attached like small adhesive bandages to critical structures. With a battery-less, wireless, network array all these sensors can be monitored continuously. Instead of disassembling an aircraft for maintenance, the sensor array could be scanned in a few seconds to determine the aircraft's overall health. Besides improving safety, the cost of maintenance and repair could be drastically reduced.

Food Safety

Recently a small amount of contaminated packaged spinach slipped into the food chain in the US. Many people became ill and a few people died from E. coli contamination. For months, consumers throughout the world shunned vegetables grown in California. The Centers for Disease Control and Prevention (CDC) estimate that 73,000 cases of Escherichia coli O157:H7, or E. coli, occur annually in the United States. Every year, 2,100 Americans are hospitalized, and 61 people die as a direct result of E. coli infections and its complications. A recent study estimated the annual cost of E. coli O157:H7 illnesses to be \$405 million (in 2003 dollars)[1]. Now imagine an entire crop in the field being monitored for contaminants with an array of tiny inexpensive battery-less micro-spectrometers capable of identifying chemicals and biological agents. Perhaps the sensors will be so inexpensive they will be included with food packages to give consumers the assurance they need prior to consumption. Such a system is not feasible with current technology due to the complexity and cost of the sensors. As the technology of MEMS (Micro-Electro-Mechanical Systems) and micro-electronics advances, however, this may one day be the norm for delivery of fresh vegetables from field to market.

Life in the Network

We generally think of networks as the office network or the internet. But what if low cost micro-sensors, capable of RF communication, and powered by micro power generators existed. They could sense heat, sound, pressure, stress, humidity, infra-red radiation, etc, and communicate that data to where it is needed for appropriate reaction. These autonomous sensors would operate indefinitely without batteries.

How would this technology benefit us? These sensors would report the condition of the wings on an airplane, preventing structural failures. The bridge on the highway would monitor stresses and provide advanced warning of possible failures. Was there a minor accident on the highway up ahead? The network would know. Is someone trespassing on private property or illegally crossing our borders? The tiny unseen sensors would immediately report the location of the intruder. Using low cost micro-sensors, networks with thousands of sensors might be built. With today's need for batteries to power wireless networks, this scenario is limited to a few applications. Not only do the batteries wear out, but they must be replaced to maintain the integrity of the network. Even if micro-batteries were developed, it would only be economically feasible to replace the batteries in very high-end expensive systems.

A Network Solution

Wireless networks are growing in our homes and offices. Because of the introduction of low power networks such as WiFi, ZigBee, and MiWi, many new applications of monitoring our environment have become possible. Currently these systems require batteries to power the electronic sensors and to wirelessly broadcast their information to the central controller. Instead, imagine a network of tiny battery-less wireless sensors communicating with each other over a network. As mentioned above, the sensors might sense stresses throughout the beams and columns of a highway bridge. This sensor array would continuously monitor the structural integrity of the bridge. A battery power monitoring system containing even 20 to 50 sensors would be unimaginably difficult to maintain. The sensors envisaged by this future network instead would contain no batteries. They would sense the stress level in the structure to which they would be attached and they would wirelessly communicate the stress to a master control unit. They would be attached adhesively to the beams and columns much like bandages. They would gather their power from vibration, temperature difference, light, wind, or sonic vibrations depending on the actual environment.

About ZigBee

ZigBee is one of a number of low power network communication protocols. ZigBee is the name of a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard for wireless personal area networks (WPANs). ZigBee operates in the industrial, scientific and medical (ISM) radio bands; 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz in most jurisdictions

worldwide. The technology is intended to be simpler and cheaper than other WPANs such as Bluetooth. The most capable ZigBee node type is said to require only about 10% of the software of a typical Bluetooth or Wireless Internet node, while the simplest nodes are about 2%. However, actual code sizes are much higher, closer to 50% of Bluetooth code size. ZigBee chip vendors have announced 128-kilobyte devices.

About Micro-Energy Harvesting [2]

A variety of environmental sources of energy exist such as sunlight, thermoelectric conversion (requires a temperature difference between two points), vibrational excitation, and power from human input.

Solar cells—100mw/cm² in bright sunlight

This is a strong candidate even for power to a ZigBee node. Unfortunately, sunlight is not always available in many cases.

Thermoelectric— 60μW /cm²

Thermoelectric generators require a temperature difference between two points. This is sometimes difficult to find in practice; although, Seiko at one time manufactured a thermoelectric watch utilizing the difference in temperature between the user's wrist and the case.

Vibration--150μW to many mW depending on size and amplitude of vibration

A recent analysis indicates that we can expect up to 4μW /cm³ for vibrational micro-generators for human motion (5mm motion at 1 Hz) and up to 800 μW /cm³ for machine-induced stimuli (2nm motion at 2.5 kHz) [2]. The author goes on to say that these estimates surpass current device performance by between one and three orders of magnitude, so there is plenty of room for improvement.

People power—150μW for heart beats [3] to 250-700mW for walking

A piezoelectric generator built into a shoe by James Antaki and his collaborators at the University of Pittsburgh was capable of 250-700mW while walking and over 2 W when jogging. While this is a relatively high level of power, it is often difficult to get the power from the person foot up to the point where the sensor is located since wires must be used or the power must be induced by large coils.

The Missing Link

So why can't these wonderful networks of battery-less sensors be built today? Environmental vibration is probably the most ubiquitous source of energy and the best choice for an energy source for application such as bridges, airplanes, people power, and vehicles. But the amount of energy available from vibrational sources is small in most

cases. The power required for a ZigBee sensor node is between 54-80mW in transmit mode and 520 μ W in sleep mode. Clearly ZigBee requires too much power and vibration micro-energy harvesters (150 μ W) that have been built to date are not very efficient. For this perfect marriage of sensors and networks to work, better more efficient designs for vibrational micro-energy harvesters must be built and extremely low power networks must be devised. Micro-systems provide the potential to build tiny, low cost, robust, power generators that can utilize multiple energy sources, solar, thermal, and vibrational. The network might be called ELPWiN or Extremely Low Power Wireless Network.

Conclusion—Building the ELPWiN Network

The authors believe that by using recent advances in piezoelectric materials and fabrication technology for energy harvesting, along with the development of a network of sensors nodes that share their power interactively, the low power networks described above can indeed be realized. The Center for Integrated Manufacturing (CIM) at the Rochester Institute of Technology is currently developing large networks involving sensors for a variety of civilian and military applications. Infotonics Technology Center (ITC) in Canandaigua, NY has extensive MEMS development and manufacturing capability and is currently developing micro-sensors for pressure, strain, and temperature. By joining together, these two institutions are well positioned for development of ELPWiN. CIM and ITC are currently seeking funding to fully realize the ELPWiN vision proposed in this white paper.

References

- [1] Frenzen PD, Drake, A, et al. Economic cost of Illness due to Escherichia coli O157 Infections in the United States. J Food Prot, Vol.68, No.12, 2005, pgs 2623–2630.
- [2] Paradiso, Joseph A., Starner, Thad, “Energy Scavenging for Mobile and Wireless Electronics,” PERVASIVE computing, www.computer.org/pervasive, Jan.-Mar. 2005.
- [3] US Patent 3,456,134.

A Word about the Authors

About Infotonics and its staff

The Infotonics Technology Center, a 501(c)(3) not-for-profit Corporation, is an industry-led, collaborative organization focused on the commercialization of microsystems technologies. Infotonics was created through a unique partnership of Corning Incorporated, Eastman Kodak Company and Xerox Corporation who combined forces to establish a leveraged R&D and pilot manufacturing facility in the area of microsystems technology. Investment by the State of New York and the

Federal Government added to the Center's resources and allowed expansion into new markets and technologies.

Infotonics now possesses a capital equipment infrastructure that will be difficult for any other region or state to duplicate. The Center occupies a 120,000 ft² building that formerly housed a Xerox facility. Approximately 23,000 ft² of clean room space has been renovated to provide 12,000 ft² of Class 100 clean room and another 11,000 ft² of Class 1000 support space. Microsystems device fabrication equipment valued at over \$40 million has been installed and activated in this clean room space. The equipment was selected to provide a highly flexible and comprehensive capability for the development and pilot-scale production of microsystems (micro-optical, micro-electro-mechanical and micro-fluidic) devices based on state of the art silicon or glass microfabrication processes.

Infotonics' working model was founded upon university-based partnerships that provide access to scientific expertise within our network of 18 New York State colleges and universities. For example, the following academic partners have provided broad scientific or engineering expertise to fill research or engineering gaps: Alfred University, City University at New York, Clarkson, Columbia University, Cornell, Rensselaer Polytechnic Institute, Rochester Institute of Technology, Syracuse University, University of Buffalo, and University of Rochester. Infotonics leverages the strengths and capabilities resident at the universities to provide highly specialized expertise on project challenges. If needed, several of these universities have medical schools, materials science, ceramics, MEMS and other departments. **Infotonics is dedicated to transitioning technologies out of the lab and into the marketplace.** Our staff works with university researchers to prepare and design concepts for future production.

About CIMS and its staff

The Center for Integrated Manufacturing Studies (CIMS) at RIT was established in 1992 with the mission to increase the competitiveness of manufacturers through applied technology and training. CIMS represents a dynamic collaboration of in-house technical experts, as well as academic, industry and government resources.

CIMS' major programs include:

- Sustainable Systems Research Center
- National Center for Remanufacturing and Resource Recovery
- Systems Modernization and Sustainment Program
- Manufacturing Technologies Program
- Occupational Safety and Ergonomics Excellence Program
- Center for Excellence in Lean Enterprise
- Imaging Products Laboratory

CIMS' 170,000 square-foot facilities, which house \$45 million of contemporary equipment, on the campus of RIT support solution developments in technology

bays, specialized applied technology laboratories and a state-of-the-art training center. Over the last two years, CIMS has interacted with some 1,000 companies, completed over 1,100 industrial projects and conducted more than 600 training courses for over 12,000 participants from around the world.

The Systems Modernization and Sustainment Program (SMS) at CIMS has demonstrated significant success in enhancing the performance of commercial and military equipment and support systems, while smartly managing total life cycle costs. The program provides expertise in the area of asset health management technologies which is designed to monitor equipment health and predict future failures for reduced operating costs and longer equipment lives. Research is also being conducted on material aging which characterizes how and why materials fail in order to advance the technologies and keep equipment operating longer and more reliably.

Within three state-of-the-art research bays and several laboratories, SMS develops technologies and methodologies for applied research, facility and process assessments, training, and technology transfer.

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