Energy Harvesting

White Paper

by Dan Steingart and Joe Polastre

Introduction

Businesses are extracting value from pervasive computing through never before seen insight into their facilities, assets, and equipment. Pervasive computers can be anywhere, and attached to anything in the world around us. Industries are adopting pervasive computing in wide ranging applications from residential power meters to cornstalks to pacemakers to jet engines. Due to the remote, real-world nature of pervasive computers, deployments seek to minimize costly maintenance. As these designs progress, businesses must plan for maintenance in their cost of ownership, leading many companies to consider scavenging energy from the environment monitored by the pervasive computer. Many customers seeking pervasive application solutions ask, "How often will the batteries need to be changed?" Wouldn't it be nice if the batteries *never* needed to be changed?

Energy harvesting technologies, when properly implemented, greatly reduce and sometimes eliminate node maintenance. These methods are cost competitive with batteries on a per-unit basis, and can readily be attached to pervasive computing solutions. The terminology and technical details of these techniques can be confusing; this white paper provides guidelines to help select an energy harvesting technology.

Three popular forms of energy harvesting are photonic (such as harvesting light from the sun), thermal (such as harvesting waste heat from manufacturing), and vibrational (such as harvesting energy from engine oscillations). While these methods offer "free energy", it is important to understand the strengths and weaknesses of each method to identify appropriate environments and application conditions for an energy harvesting solution. This white paper summarizes the principles and implementations of modern energy harvesting techniques, and provides guidelines for integrating energy harvesting technologies with pervasive computers.

Figure 1 A solar-powered pervasive computer analyzing the condition of H/VAC equipment at Sentilla's headquarters in Redwood City, California.

Baseline Power Requirements and Size Factors

Pervasive networks have a wide range of sensors and application possibilities, which also means they have a wide range of power requirements. Before we discuss energy harvesting methods, it is important to understand the basic operating power requirements of a pervasive computing solution.

For this example, we will use a median power requirement as baseline, which includes products from Sentilla as well as other vendors. An average power consumption per node of 600 μW to 1 mW is typical for a representative cross section of low duty cycle, ad-hoc, multi-hop wireless networks. To ease the math and err on the side of caution, we will assume an average of 1 mW power consumption. For reference, a pair of standard alkaline AA batteries could power our 1 mW device for roughly 100 days without DC-DC conversion.

Nodes in most applications that Sentilla has deployed are generally the size of a 12 ounce cola can (355 cm^3), so we will use the cola can paradigm throughout this paper to ease visualization.

Primary Batteries as a Control Case

Before we investigate methods for deriving energy from the environment, let us also consider D cell alkaline cells, which can be anywhere from $0.50 to $1.00. This cell typically provides over 20,000 mWh[1], which is over two years of runtime for our application. Alkaline cells, however, must be used in pairs or with a voltage doubler to provide the required operating voltage for pervasive computers. Alkaline cells generally lose capacity at a rate of 4% a year at room temperature, thus, there are diminishing returns for increasing battery volume.

If shelf life is a concern, a D cell lithium sulfur costs more than a D cell alkaline, but may come with a guarantee to work for 10 years. A lithium sulfur dioxide cell provides over 20,000 mWh of energy[2], thus, our 1 mW application would last over two years on a single cell. With our volume constraints, if we have relatively small sensors, we may be able to use two of these cells, so the runtime effectively doubles to over four years (1660 days).

Batteries also provide a distinct design advantage. Systems powered solely from a primary cell do not require environmental coupling. This allows the user to place the device almost anywhere without concern. Also, decoupling makes predictive maintenance easier as batteries are within ±5% of their predicted capacity.

However, batteries have design drawbacks as well, outside of replacement. Alkaline batteries have a relatively limited temperature range. The rate of self-discharge increases significantly with temperature, and these cells simply cannot be used for any duration with temperature in excess of 50°C. Lithium sulfur dioxide cells provide better temperature behavior and shelf life, but also vent SO_2 gas during use, so applications where effluence is a concern may shy away from these cells. Always check that the environment is compatible with your batteries.

Battery Guidelines

Primary batteries should be considered when:

- The application lifetime is two years or less.
- The application is generally in a dark, cool, quiet location, such as shady forests or mines.
- Mobile applications where the environment may change often or unpredictably.

Photon Harvesting

Given a clear sky almost anywhere in the continental United States, harvesting light from the sun is by far the easiest path to "free energy". These systems have been used on a large scale for years: whether for security lights, traffic signs, or home energy. Solar cells come in a variety of shapes and sizes, but in most climates, a cell approximately the size of a credit card is sufficient for pervasive computers.

---

[1] http://www.duracell.com/oem/Pdf/others/ATB-5.pdf

[2] http://www.saftbatteries.com/MarketSegments/Aircraft/tabid/362/tabid/300/TypeControl/Produit/ProduitId/25/Default.aspx

Pervasive computers have been powered by solar cells in the following applications:

- crop monitoring to enable better use of water supplies,
- outdoor asset tracking to keep track of the condition and location of valuable units
- environmental studies to monitor air and water quality.

The most familiar form of photon harvesting is through the use of solar cells. With a solar cell the size of a credit card, sunlight provides a daytime average of 100 mW[3.]. This power can readily be achieved with a polycrystalline silicon photovoltaic for about $10 USD. Single crystal silicon cells provide better conversion efficiencies, resulting in power output increases of up to 50% when compared to polycrystalline, but single crystal silicon cells are an order of magnitude more expensive for a given area (as much as $100 per cell). For our cola can application, the power provided by polycrystalline silicon is more than sufficient. Alternative materials are being introduced to the market, and may provide a cost advantage. Regardless of technology, solar cells can vary widely by manufacturer, so be sure to test the efficacy of a cell before committing a design around it.

Solar energy is closely related to the angle of incidence, so at dusk and dawn the power may be 10 mW for our test cell, while at noon the available power is 200 mW. If the device must function continuously, it is important to design a secondary power source which can collect extra energy for use overnight or when available sunlight is insufficient to power the node. Indoors, these cells fare poorly, generally requiring almost 10 times the surface area needed to meet the 1 mW continuous energy requirement. Industrial environments are especially poor as illumination levels are low and chances of debris obstruction (for example, dust that collects on the solar cell) are high.

Photovoltaic cells generate consistent DC power; simple power electronics are needed to match the potential requirements of a pervasive computing system. The most basic circuit would involve photovoltaic modules placed in series to match the node's required potential, and with a simple comparator to prevent brownout conditions. More advanced circuits may use a larger area single cell and a boost converter, or more cells in series and a regulator or buck converter. These options provide better conditioning for the unit.

Other qualitative issues with photovoltaic harvesting involve ensuring the integrity of the unit. Care must be taken to prevent overheating of a cell. Temperature ranges differ by manufacturer, but the insolation and ambient temperature of the deployment environment should be clearly understood before a long term installation is to take place. When installed, the cell should be placed in a such a way as to prevent long term solar obstructions, and, if possible, to minimize debris collection. When operated within specified conditions, manufacturers guarantee the work life of these cells generally for 25 years[4], but cells may occasionally need to be cleared of debris. By measuring the loaded potential of a photovoltaic cell during operation, as well as the intensity of the illumination (with a photo diode, for example), debris accumulation can be estimated and maintenance scheduled. This maintenance may be as simple as hosing down a cell or as involved as using a sponge.

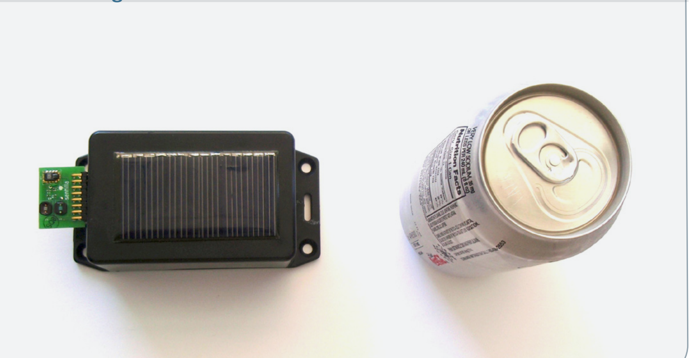
Overall, photovoltaic cells are a clear choice for outdoor installations where node lifetime must surpass five years, provided a clear view of the sky. Secondary concerns such as power circuitry and batteries are tractable issues that must be considered on an application-by-application basis. Photovoltaic systems do not offer a clear advantage indoors, where line power, primary batteries, or other forms of energy harvesting can achieve better results with smaller form factors.

---

[3] http://www.duracell.com/oem/Pdf/others/ATB-5.pdf

[4] http://www.solarelectricsupply.com/Solar_Panels/Shell/shell-solar.html

Figure 2
A solar-powered Sentilla-enabled environmental monitoring node.



Photonic Harvesting Guidelines

Photonic harvesting should be considered for applications where the node is outside and exposed to at least five hours of sunlight (direct or cloud cover), whether mobile or stationary. A DC-DC converter should be used to ensure efficient potential regulation regardless of sunlight, and a secondary battery with sufficient overcapacity should be placed in parallel to allow the pervasive computer to remain functional during dark periods. Remember, the pervasive computer is aware of its environment so programming light-based responses can further extend system life and measure solar harvesting efficiency.

You may also need to consider whether the application is deployed in an area that collects significant dust or debris.

In Action

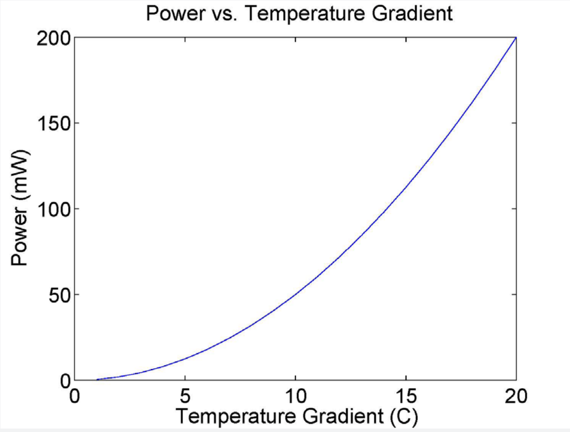
Sentilla has deployed motes that measure temperature, insolation, and humidity outside with a very small form factor (10 cm x 5 cm x 4 cm) that run continuously, powered by a 7 cm x 4 cm solar panel in parallel with a 6 cm x 4 cm x 3 mm lithium ion battery (Figure 2). The battery receives a net positive charge each day. In fact, the California sun is so powerful that the battery must be protected from overcharging!

Thermal Harvesting

Temperature gradients exist between nearly any object doing work and its environment, and elementary thermodynamics dictates that any temperature gradient has an associated power dissipation. This means that, in theory, any surface that feels hot can be used to produce electricity. Manufacturing applications, where heat is a by-product of the manufacturing process, are typically ideal applications for thermal energy harvesting.

Thermoelectric devices can directly convert thermal gradients into electrical power without pumps or a working fluid, relying on semiconductor physics to drive the process. While thermoelectric devices are not as efficient as devices like sterling engines, they also require a fraction of the components than those of a mechanical solution, and require no generator to convert mechanical energy to electrical energy. This mechanical simplicity is an added advantage for pervasive computing applications due to cost, size and durability, so we restrict our exploration to thermoelectric devices.

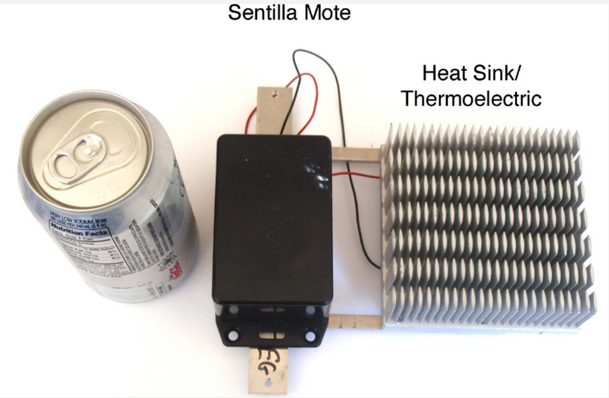
Figure 3
Maximum power vs temperature from a Tellurex thermoelectric device.



Two major requirements of thermoelectric harvesting are a hot surface and a sufficient heat sink. Bismuth telluride is the standard material for thermoelectric elements, and has a maximum operating temperature of 175˚C[5]. Power output scales as the square of the temperature gradient, so over an area of 25 cm^2 the power will scale as shown in Figure 3. The gradient described in Figure 3 refers to the actual temperature across the thermoelectric element, and not the temperature of the hot surface compared to the ambient temperature. The gradient across the thermoelectric element will always be less than the maximum, therefore, a good heat sink design is critical for these applications to extract the maximum power possible.

Thermoelectric elements, like photovoltaics, produce DC power. Unlike photovoltaics, DC-DC conversion is almost always necessary to provide stable potentials, as the potential of the thermoelectric module depends strongly on the effective gradient. Buck-boost converters are readily available and highly effective, allowing a system to run as long as the heat source is available.

Figure 4
A Sentilla-based computer from Wireless Industrial Technologies for use in a primary aluminum smelter.



Most industrial operations that produce temperatures sufficient for thermal harvesting tend to maintain a constant temperature, and if the unit is not operating, measurements are generally not required. Secondary batteries are usually superfluous for thermal harvesting designs. This is a lucky coincidence, as most batteries cannot operate under extreme temperature conditions. If needed, batteries can be designed into such a system, but they must be thermally isolated.

Once a unit is installed, it is generally maintenance-free unless the heat sink is located in an area that accumulates significant debris.

Thermal Harvesting Guidelines

Thermal harvesting can be implemented on hot structures by using a heat sink and DC-DC converter. You should consider this method if:

- Your application is very hot or scalding to the touch.
- There is enough space to place a large (1 inch thick) heat sink.
- Your application surface is uniform and smooth.

In Action

Sentilla nodes built and deployed by Wireless Industrial Technologies (WIT)[6] are powered solely by thermal harvesting. Deployed in aluminum smelters to monitor the production process, the massive heat emitted powers the entire pervasive solution (Figure 4).

The nodes are measuring quantities previously too costly to instrument, including pressure, temperature, current and potential across a production line that spans one linear mile.

---

[5] http://www.tellurex.com/cpowermod.html
[6] http://www.wirelessindustrialtechnologies.com

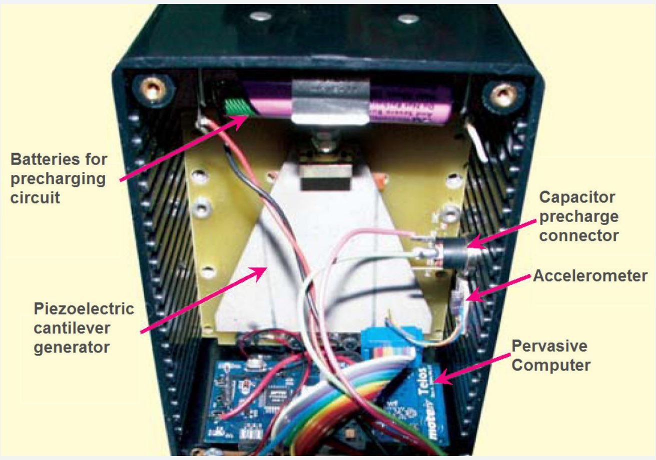
Vibration Harvesting

Vibration harvesting represents perhaps the ultimate utilization of process entropy using the by-product of motion to power subjugate devices. It is also the most difficult to realize. To maximize power generation, we must provide the tightest coupling of the node to its environment, as the harvesting device is inherently mechanical and subject to all failure modes of moving objects. Even with these drawbacks, environments with constant vibration like motors and engines can be well-suited to vibration harvesting.

Available vibration harvesters typically rely on two methods for generation: electromagnetic induction or piezoelectricity. Electromagnetic induction is analogous to a standard motor, but rather than use a magnet that spins continuously, it moves back and forth through a stationary coil. Piezoelectric generators are cousins to microphone elements, and rely on materials that produce a field upon mechanical strain. They are typically cantilevers with a mass on the free end.

Figure 5

A pervasive computing solution from Rockwell Automation powered by vibration that monitors the health of motors.[7]



While piezoelectric systems are mechanically less complex than electromagnetic systems, electromagnetic systems are traditionally less likely to fail when subjected to large accelerations.

Depending on the acceleration force on the object and the frequency of vibration, both types of harvesters will produce on the order of 0.1 mW to 10 mW continuously, given our cola can constraints.

Both harvesters are dependent on reliable modes of vibration, and each must be tuned to a particular frequency before installation. Most units produce 90% *less* power if the frequency shifts by only 5%.

Vibrational methods are inherently AC, therefore, power circuitry must always be in place to rectify and regulate the signal. In our cola can size node, rectification circuitry needs an insignificant amount of space, but as form factors decrease, efficient rectification becomes a size limited effort.

Vibrational harvesters thrive in environments with reciprocating equipment. That is it works well with equipment that vibrates noticeably and consistently. This makes it a promising method for industrial monitoring where equipment is often mechanically tuned to ensure proper operation. In contrast, vibrational harvesters are difficult in mobile applications where structural vibrations may vary with velocity and noise.

Vibration Harvesting Guidelines

Can you feel noticeable vibrations when you touch the surface of your equipment? Does your application vibrate at a consistent predictable frequency? If it is a pump, fan or other motorized device, it probably does. If it rattles with a random distribution of frequencies, vibration harvesting will not likely provide the power that pervasive computers needs.

---

[7] http://necsi.org/events/iccs6/papers/7df7ed07961c3fb28cfd2f851d82.pdf

In Action

Sentilla nodes, modified by Rockwell Automation[8] and powered by environmental vibrations, have been successfully run on pumps and other machinery on oil tankers. These sensors measure the nature of the vibrations that provide the power, and enable predictive maintenance algorithms to be established for critical machinery aboard ships (Figure 5).

Secondary Power

For supplementary power, a secondary battery can be placed in parallel with the harvesting module. The complexity of the coupling circuit depends on the chemistry of the battery. When cycled properly, Nickel Metal Hydride (NiMH) cells have demonstrated over 1,000 cycles[9]. Cycled every day and night in a solar harvesting system, that is a lifetime of almost 3 years. However, these cells must be managed carefully to maintain capacity, and they are prone to the same temperature and self-discharge deficiencies of alkaline primary cells.

Lithium ion cells exhibit radically different cycling behavior. These cells, when fully discharged on each cycle, provide 500 to 2000 cycles, depending on the chemistry. However, studies[10] suggest that if a cell is discharged lightly on each cycle (10% of overall capacity or less), cycle life can be extended to 5,000 cycles, or about 13 years.

The limiting factor with these cases is not battery failure due to standard reasons, but rather because of operating outside of designed temporal life. Lithium ion batteries, when manufactured correctly, should be able to cycle lightly for 10 years or more, but the supplier should be scrutinized carefully to see if their assembly methods are sound.

Questions to consider are:

- What is the capacity stability over various temperature and humidity conditions?
- Will the manufacturer guarantee the shelf life to 10 years? 15 years?
- Does the manufacturer have data on cycle life as a function of depth of discharge?

If the manufacturer cannot answer these questions, chances are their products are simply not built to last the length of your application, regardless of the depth of discharge you are placing on the cell.

In Action

An outdoor Sentilla deployment uses a 1300 mAh lithium ion battery as a backup source to a solar cell. This cell is 6 cm x 4 cm x 3 mm. This fits readily into our cola can, and based on our 1 mW requirement, actually provides over 100 times more capacity than an overnight discharge would ever require.

Conclusions

Energy harvesting technologies do not generally compete with one another. As we have demonstrated, they each mate with a particular environment well. In fact, a given network of nodes may use each kind of harvesting.

Energy harvesting techniques available today can be used in all aspects of a modern factory, for example:

- Solar for moving asset location and condition outdoors
- Thermal for production efficiency
- Vibration for predictive maintenance of conveyor belts and factory-floor motors

---

[8] http://necsi.org/events/iccs6/papers/7df7ed07961c3fb28cfd2f851d82.pdf
[9] http://www.duracell.com/oem/Pdf/others/TECHBULL.pdf
[10] http://www.mpoweruk.com/life.htm

This simple example shows how leveraging all three methods can enable an entire factory, from production to logistics, to benefit through a reduction of maintenance and an increase in runtime. Table 1 details the methods discussed, with advantages and disadvantages, and recommends areas where each method would be well suited. This is by no means a definitive or exhaustive list, rather, a framework with which to start your design.

About the Authors

Dan Steingart is Senior Application Engineer at Sentilla. Dan holds an M.S. and a Ph.D. in Materials Science and Engineering from University of California, Berkeley where he developed printed microbatteries for pervasive computers, and an Sc.B. with honors in Engineering from Brown University. Since then, Dan has developed pervasive computing applications that save electricity in aluminum smelters, reduce heating bills in homes, and protect firefighters.

Joe Polastre is Co-founder and Chief Technology Officer at Sentilla. Joe is responsible for defining and implementing the company's global technology strategy and for orchestrating Sentilla's product road map. He holds an M.S. and Ph.D. in Computer Science from University of California, Berkeley, and a B.S. in Computer Science from Cornell University. Joe sits on numerous technical boards and commissions and is regularly sought by industry forums to speak on pervasive computing. Joe was among the pioneers of the pervasive computing industry while at University of California, Berkeley, and deployed the first and largest applications. Before joining Sentilla, he held technical positions at IBM, Intel, and Microsoft.

About Sentilla

Sentilla provides a software solution that is at the core of numerous commercial applications that are transforming the way organizations are managing energy, logistics and infrastructure. For example, by embedding intelligence in the world around us, Sentilla's award-winning pervasive computing solution analyzes energy efficiency in real-world conditions directly where energy is consumed. With this insight, industries are minimizing their global energy footprint, optimizing their production processes, and taking action before problems become disasters. Founded in 2003, Sentilla Corporation is based in Silicon Valley and privately funded by ONSET Ventures and Claremont Creek Ventures. For more information, please visit the Sentilla website at www.sentilla.com.

Table 1 Comparison of various pervasive computing power sources

	Advantages	Disadvantages	Application Area
Photonic	Cost effective Size effective Durable DC Power	Does not work well indoors Prone to failure by debris Requires secondary storage for 24/7 uptime	Agriculture Shipping Yards Outdoor security Transportation
Thermal	Works where batteries cannot Adaptable Active whenever the object to be measured is active	Requires large thermal gradients Requires bulky heat sinks	Monitoring industrial exhaust Furnaces Engine/Powertrain
Vibrational	Has the potential to work anywhere there is machinery, regardless of temperature or illumination Frequency can be tuned for a specific application	Highly frequency dependent Requires excellent mechanical coupling Requires rectification Currently expensive	Machine tool monitoring Pump monitoring Engine monitoring