Energy harvesting – small scale energy production from ambient sources

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ABSTRACT

Energy harvesting – the collection of otherwise unexploited energy in the local environment – is attracting increasing attention for the powering of electronic devices. While the power levels that can be reached are typically modest (microwatts to milliwatts), the key motivation is to avoid the need for battery replacement or recharging in portable or inaccessible devices. Wireless sensor networks are a particularly important application: the availability of essentially maintenance free sensor nodes, as enabled by energy harvesting, will greatly increase the feasibility of large scale networks, in the paradigm often known as pervasive sensing. Such pervasive sensing networks, used to monitor buildings, structures, outdoor environments or the human body, offer significant benefits for large scale energy efficiency, health and safety, and many other areas. Sources of energy for harvesting include light, temperature differences, and ambient motion, and a wide range of miniature energy harvesters based on these sources have been proposed or demonstrated. This paper reviews the principles and practice in miniature energy harvesters, and discusses trends, suitable applications, and possible future developments.

Keywords: power sources, wireless sensors, energy scavenging

1. INTRODUCTION

Energy harvesting, or energy scavenging as it is also known, refers to the generation of electrical energy using sources present in the local environment. Generally these are transient sources, such as air flow or sunlight, and in this sense energy harvesting is clearly distinct from electrical generation involving the consumption of non-transient sources such as fossil fuels. However, energy harvesting usually also suggests small scale energy production, where the energy use as well as the source is local. In this way it can be distinguished from the use of ambient, transient sources such as wind, waves and sunlight for large scale power generation. Because such sources are inexhaustible, their use at large scale is becoming increasingly important for sustainable energy supply. Interest in energy harvesting is also growing, primarily as a result of the increasing proliferation of mobile and distributed electronic systems and devices, and the resulting need for convenient power sources for these.

Some energy sources are applicable both for large scale production and for small scale harvesting – most importantly, solar power and air flow. A number of other sources are used for harvesting which are impractical at larger scales. Besides the inherent size dependence of sources and conversion mechanisms, a key difference is that for harvesting, the source must be in the immediate environment of the application – the application can generally not be relocated in order to access the energy source. This creates a strong dependence on the particular characteristics of applications, and so has led to a diverse range of harvesting approaches being developed.

Energy harvesting sources for portable electronic appliances such as cellphones and laptop computers would certainly be attractive to consumers. However, the required power levels – ones to tens of watts – are well beyond what appears to be practical from harvesters of appropriate size. Consequently, practical efforts have focused on applications requiring much less power, and these are dominated by wireless sensors of various kinds. Generally, reported harvesting devices have dimensions from a few cm to sub-mm, and output powers from sub-microwatt levels up to a few milliwatts. Clearly, such devices cannot have a direct impact on the world’s energy needs; the world electricity generation capacity is several terawatts, and about 10^{11} of the largest energy harvesters reported would be needed to replace a single large scale power plant. Cost also compares unfavorably; for example, a 1 mW harvester operating continuously for 10 years will generate about 0.1 kWhr. This is worth only about 1¢ at current consumer prices, although the cost of 0.1 kWhr in the form of primary batteries is much higher at about $10. Indeed, batteries are usually the alternative to energy harvesting, and simple cost or size saving is unlikely to provide a sufficient advantage for the latter. Generally, the motivation for avoiding batteries will be the impracticality of battery replacement or recharging, as a result of the remoteness or inaccessibility of the devices. In addition, there is increasing interest in networks of very large numbers of sensors and other nodes ("pervasive sensing"), and in such scenarios the sheer number of batteries required makes their maintenance impractical even if there are no accessibility issues.

2. REQUIRED POWER LEVELS

Power consumption in wireless sensors can be portioned according to the four main functional blocks of the device: the sensing itself, signal conditioning and processing, data storage, and communication. This is illustrated in Fig 1. We will consider each of these in turn.

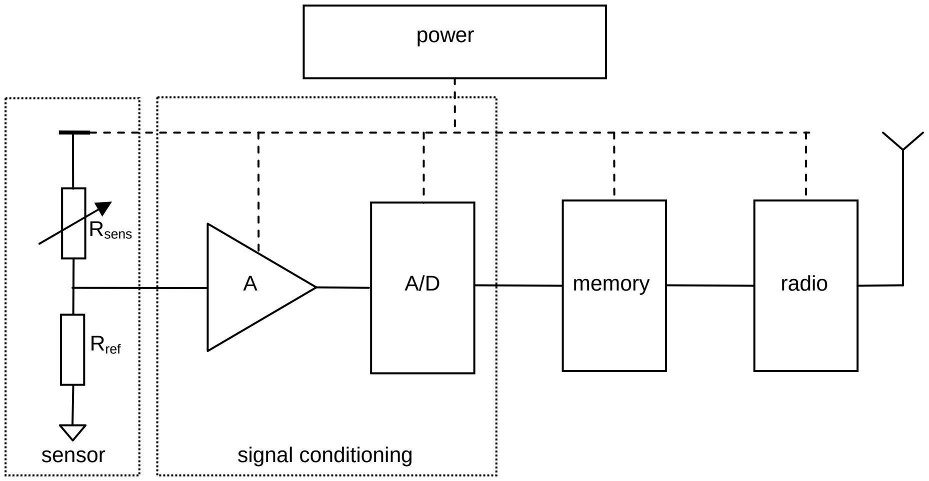

Fig. 1. Block diagram of a wireless sensor node, showing the principal functional elements.

2.1 Sensing Elements

Clearly there are a vast number of sensor types, for measuring a large number of quantities, and so the power requirements are highly variable. Some sensors require provision of power to the target: for example, a radiation source for active spectrometry, or a current source for an electrical conductance measurement. Multi-dimensional sensors, particularly video monitoring and other dynamic imaging techniques, also tend to have high power requirements. In addition, high bandwidth sensors such as video place correspondingly high power demands on the subsequent processing, storage and transmission functions. However, many important sensing applications require only a passive, low bandwidth sensor of one or few dimensions of output.

In Fig. 1, the sensor is represented as a variable resistor; when a bias voltage is applied to this in series with a reference resistance, a voltage signal is obtained. A number of common sensors are of this type, including thermistors for temperature measurement and piezoresistors for pressure or strain measurement, although the circuit implementations in practice are typically more complex than in Fig. 1. Some power must be drawn from the bias voltage source to obtain a signal, and this must exceed the thermal noise power of 4kT per unit bandwidth. In fact, in the circuit shown, and assuming the sense and reference resistors are matched, the bias power must be higher than the noise power divided by the fractional change in the sense resistance squared to get a signal to noise ratio (SNR) of 1. However, since 4kT at room temperature is only 1.6×10^{-20} W/Hz, and many sensors only require modest bandwidths, the bias power can still be very small. For example, for a fractional deviation in R_{sens} of 0.1%, a bandwidth of 100 Hz and a SNR of 10 dB, the minimum bias power is only 10 pW, which we can consider as negligible. Actual sensor biasing power will be limited by practical constraints on bias voltages and R_{sens} values, and is more likely to be in the region of μW.

Sensors that generate output signals without bias power, such as thermocouples or piezoelectric strain sensors, will also have thermal noise considerations, although these cannot be decoupled from consideration of the initial signal conditioning stage, where amplification to a suitable level for further processing is a typical requirement. Never-the-less, for typical sensor bandwidths, the power requirements resulting from thermal noise will be negligible. Other noise types, such as 1/f noise, will have power levels specific to the sensor type and input circuitry.

2.2 Signal Conditioning

Digitization of the signal is almost certain to be a minimum requirement for signal conditioning, as it is essential for data storage, and data transmission is almost certain to be digital. Fortunately, very low power analog-to-digital converters (ADCs) have been reported. Commercially available devices typically consume mW of power, but there are devices available consuming below 100 μW. In addition, these generally provide much higher sampling rates than are required in most sensor applications, and power consumption reduces roughly linearly with clock rate. By operating at very low supply voltages (i.e. 0.5 V), Sauerbrey et al. achieved a power consumption below 1 μW for an 8-bit ADC operating at 4 kS/sec. [1].

Some amplification is likely to be required to bring the signal into a suitable range for A/D conversion. This amplifier can also perform the task of low pass filtering to exclude out-of-band noise and avoid aliasing. Generally such circuits consume little power. Maxim, for example, have operational amplifier chips available which draw 7 μA for 2.4 – 7 V single sided supply, i.e. as low as 17 μW [2]. Holleman and Otis recently reported a sub-microwatt amplifier for neural recording with 36-44 dB gain, and a passband of 0.3 Hz to 4.7 kHz [3]. Additional power saving can be achieved by monolithically integrating sensor node functions. Teo et al. reported a chip for wireless health monitoring applications which incorporates an amplifier, ADC, and additional digital processing, while drawing only 7.5 μA from a 0.9 V supply [4]. Clearly, sensor signal conditioning using microwatt power levels is not just feasible but an established fact.

2.3 Data Storage

In principle, sensing applications can be imagined where signals are transmitted to a remote location immediately, without any need for local storage. However, a number of factors suggest that this will usually be impractical. Depending on the communication protocol used, the digitized data will probably need to be marshaled into packets, and combined with handshaking data, and this will require at least a small amount of short term memory. Furthermore, to make effective use of transmitter power, transmission data rates will often far exceed collection rates, so that the communication will be operated with a low duty cycle, and this also necessitates memory. Finally, the communication module is likely to have the highest power requirements in the system, quite possibly exceeding the supply potential of an energy harvester. However, energy harvesting may be suitable for long term self-powered data collection and storage, with data collected occasionally by a reader which can deliver power for the communication wirelessly, as is done in radio frequency identification (RFID) systems. In such a case, enough memory for all the data gathered between data collections is clearly essential.

Fortunately, low power memory is abundantly available. For dynamic memory, e.g. for use in the packet assembly scenario, volatile memory such as static RAM may be suitable. As an example, Brilliance Semiconductor supplies a low power 64k × 16 bit static RAM chip with 20 nW standby power, for a supply voltage of 2 V [5]. Operating current is much higher at 2 mW, but it is likely that read/write operations will be very short, leading to a very low duty cycle. For longer term data retention, non-volatile flash memory is suitable. Atmel have, for example, a 16 Mbit flash chip with 10 mA active current (1.8 V supply) and 15 μA standby, with a word programming cycle being only 10 μs long [6].

2.4 Data Transmission

It is generally assumed that communication will be the most power hungry part of a wireless sensor node. Certainly for currently implemented nodes, this is generally the case. However, this is partly because available chip sets are highly over-specified for most sensor applications, particularly in terms of data rate. For example, the LM-400 Bluetooth chip from LM Technologies supports up to 3 Mbit/s, and has a transmit power of 15 – 18 dBm, but both are well in excess of what sensors will typically require, particularly for short range transmission, and the power consumption is over 300 mW [7]. In the Zigbee protocol the data rates and transmit power are reduced; the Atmel AT86RF230 consumes about 30 mW at its maximum transmit power of 3 dBm (2 mW) [8]. An ultra-low power Bluetooth standard has also been developed, sometimes called Wibree, and chipsets are starting to appear for this.

None of these come close to the ultimate limit for low power data transmission. At very low data rates the minimum transmit power ceases to depend on bit rate and becomes a function primarily of distance (and medium). Since even high bandwidth receivers can function effectively with nW of received power, transmit powers in the microwatt range should be adequate for data link distances of a few meters, as could be the case within a room, for example, or in a body area network. Also, many environmental and biomedical signals require a depth of 10 bits or less, and a sampling rate of 1/s or less, so that 10's of bits/s will often be adequate. In structural health monitoring, measurement rates of 1/hr, 1/day or even less may be more appropriate. This implies a very low overall duty cycle for the sensing device, and thus the main requirement for energy harvesting may be to power the sleep mode.

3. AVAILABLE POWER FROM HARVESTING

3.1 Solar Power

Solar cells are perhaps the most developed and established devices for energy harvesting, and provide quite substantial power levels in well lit environments. Solar cells are generally calibrated based on a nominal solar irradiation of 1000 W/m^2 (100 mW/cm^2). In practice, at least at temperate latitudes, even direct sunlight (when available) provides less than this, and diffuse light significantly less. However, with efficiencies of 15 - 20% now routinely available, and reported efficiencies surpassing 40%, output levels of ones to tens of mW per cm^2 should not be difficult to achieve in well illuminated outdoor applications during sunny conditions. In indoor environments, although light levels are more predictable, the power levels are probably 10 to 100 times less. Even this, however, is sufficient for many sensor applications, as we have seen above.

Progress in solar cell technology is driven primarily by large scale power production applications, rather than small scale energy harvesting. In the large scale case, the cell cost per unit area is a crucial factor, while for harvesting this is likely to be less important. The key to whether solar is the best solution is whether the device will receive enough light, in the right direction, for enough of the time.

3.2 Thermoelectric Power

Thermoelectric generators are also long established. Unlike solar cells they have no significant role in large scale power production, but despite this, significant technical progress has been made recently. In particular, the use of nano-structured materials has allowed figures of merit to be increased by at least a factor of two [9]. Never-the-less, a particular difficulty for small scale harvesting is that thermo-electric conversion efficiency is limited to the Carnot efficiency of $1 - T_{cold}/T_{hot}$. In small structures, where temperature differences are generally small, this implies a double penalty of low thermal power flow and low conversion efficiency. The most promising applications, therefore, are those with larger temperature differences, such as waste heat recovery on exhaust systems [9]. As an example at a smaller scale, Micropelt supply chip scale thermoelectric generators which can supply about 1 mW for a 15K temperature difference ΔT across a 6 mm^2 device, with the output power rising as the square of ΔT [10].

3.3 Harvesting from Motion

Energy harvesting from motion has been the subject of a great deal of interest and investigation in recent years, partly because of the relative ubiquity of motion in the environment. The topic is covered in extensive detail in [11], and we will only give a brief overview here. Essentially there are two forms of motion energy harvesting. The first, direct force harvesting, interposes the conversion device between two bodies moving relatively to each other, and generates electrical energy by conversion of the strain produced by this relative motion. An example is heel strike devices, which are installed in the shoe and are compressed by the force between heel and ground on each stride. The forces can be very large in such cases, and the ultimate energy available per stroke is simply this force times the device internal displacement. Other devices of this type include those that take advantage of the bending of the knee or elbow joints. However, heel strike provides a rather unique opportunity for a direct force device, and the mechanisms which must be fixed to two host structures moving relative to each other are necessarily fairly large. A potentially smaller direct force device would be a flexing transducer which takes advantage of the continuous deformation of a structure which it is attached to (or embedded within), and this can be a well suited approach for structure monitoring.

Inertial devices, on the other hand, need only be attached to a single point on a host structure that exhibits absolute motion. The principle of operation is illustrated in Fig. 2. The device contains an internal proof mass mounted on a suspension, which tends to remain stationary as the frame moves along with the host; the relative motion between mass and frame can then be damped by an energy converting transducer. The maximum energy per transit of the proof mass is its mass time the external source acceleration times the internal displacement. This results in a strong dependence of the achievable power density on source frequency [12]. It also means that if the source vibration amplitude is less than the internal motion range, resonant enhancement of the proof mass motion is needed to maximize power, and this makes the effectiveness of the device highly frequency dependent. Consequently, one theme of recent work in this area has been to develop tuneable devices that can achieve resonant enhancement but respond to variation in the nature of the source motion. For applications where the source amplitude is large compared to the size of the harvester, resonant internal operation is not required.

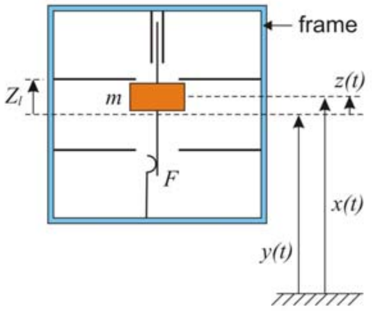

Fig. 2. Schematic of an inertial energy harvester, showing the source and internal motion $y(t)$ and $z(t)$, the energy conversion force F, proof mass m, and internal travel range Z_l.

A third form of motion energy harvesting uses fluid (air or water) flow. Air flow harvesting is simply small scale wind generation, and cm-scale wind turbines have indeed been reported [13]. Milliwatt power levels were achieved with reasonable airflows, for a 7.5 mm diameter device.

3.4 Scaling Laws

The different harvesting devices have output powers that scale differently with size. For solar cells, the power evidently scales with exposed surface area, and so with linear dimension L squared. Thermoelectric cells, if small compared to the heat source, will also have output power proportional to the area through which heat flows. However, we can also expect the temperature difference to drop with dimension in the direction of heat flow. If we approximate that the total ΔT is proportional to this dimension, and that the efficiency is proportional to ΔT, then the power scales more like L^3 than L^2.

For direct force generators, the scaling of output power is highly dependent on the assumptions made, but for example in the foot strike device, the achievable transduction force might reasonably scale with area, and the displacement with L, giving an overall scaling of L^3. Inertial devices have an output power proportional to both the proof mass and the internal displacement, and therefore the power scales as L^4. Airflow harvesters can be shown to scale even more strongly, as L^5 [13]. These different scaling behaviours are summarized in table 1 below.

Table 3. Scaling laws for different energy harvesting types.

Harvesting Method	**Dependence of Power on Linear Dimension L**
Solar cells	L^2
Thermoelectric	L^3
Direct force	L^3
Inertial	L^4
Airflow	L^5

4. APPLICATION DOMAINS

4.1 Biomedical Sensing

The many applications for energy harvesting in sensor networks that have been investigated or proposed mainly lie in one of three areas: biomedical, structure and environmental monitoring, and machine monitoring. Although each of these has a wide range of requirements, some general trends or common characteristics can be identified.

Biomedical sensors may be worn or implanted, with the latter imposing much more stringent requirements in terms of reliability and biocompatibility. In both cases the size limitations are stringent, and sensor nodes should ideally have a total size below 1 cm^3. For sensors outside the body, batteries are a suitable power source, unless replacing or recharging is especially inconvenient, for example with large numbers of sensors embedded in clothing. Inside the body, energy harvesting offers a clear advantage due to the inaccessibility of batteries. Light is not available inside the body and generally of limited availability for external sensors, which are typically below the clothes, and temperature differences are at most a few degrees, so motion based harvesting is generally seen as the most attractive. However, body motion is irregular, and of low frequency, so motion based harvesters tend to have low effectiveness and low power density.

4.2 Structural Health and Environmental Monitoring

The long term monitoring of structures such as buildings, bridges, aircraft fuselages and many others provide a well suited applications for energy harvesting as an alternative to batteries. Firstly, the desired sensor lifetime is likely to be many years, generally exceeding the possible useful life of a primary battery even at the lowest power levels. Secondly, the sensors will often be embedded in the structure, making access to batteries for replacement or recharging difficult or impossible. Finally, the desired measurement frequency will often be very low, and the need for transmission of the data even less frequent. This suits the scenario mentioned above where energy harvesting powers the data capture, conditioning and storage, but communication is powered remotely by a communicating unit which is brought into reasonable proximity to the sensor for occasional data collection. Environmental monitoring may also suit such a use scenario, and will often employ sensors in remote or otherwise inaccessible locations, and thus be a good candidate for harvesting. Many structure and environment monitoring applications will be suited to solar powering, although it should be noted that the requirement for solar cells to be exposed to the light renders them vulnerable to damage, or simply to acquiring dirt which blocks the incident light. Thermal powering will also be an option in specific cases of these sensor application types.

4.3 Machine Monitoring

Machine monitoring is somewhat more specialized than the previous areas. In addition, most machines will have electrical power available. However, bringing wired power to a sensor may be undesirable because of expense, particularly when the sensor is retro-fitted; it may also be impractical when the sensor is mounted to a moving part. Thermo-electric powering will sometimes be an option in these applications, but the environment will generally not be well suited to solar powering. Motion powering is particularly favourable in machine monitoring because the size constraints are generally not too extreme, and vibration is usually abundant, relatively uniform, and often at a well defined frequency. For this reason, machine monitoring is the application area where motion harvesting is achieving some of its first commercial successes.

5. CONCLUSIONS

In conclusion, we have seen that wireless sensors are the most attractive application for small scale energy harvesting, and that complete sensor nodes can be assembled which require only microwatt power levels in many cases. A number of harvesting sources suit these applications, primarily motion, light and temperature differences. Each has its own benefits and limitations, and we have seen that the different sources have very different size dependencies, so their relative merits depend significantly on the appropriate physical dimensions. The applications can mostly be classified into three areas, and these also have significantly different requirements and limitations.

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