Body energy harvesting for WSN. State of art, proposals and examples

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Abstract— **Wireless sensor networks are one of the most interesting ways to send and receive information from human body. These networks are composed by several nodes and these nodes can manage several sensors to acquire information from environment, giving up new services and access to new information. To reach this point, it is also very important to consider available energy sources. Everyday electronic systems reduce their power consumption but still they are not possible to work by themselves. Nowadays these systems needs external energy sources. This article goes through available energy sources that can be scavenged from human body. A proposal of WSN is made it and it is calculate a theoretical approach about feasibility of it. Finally several examples about this energy scavenging methods are presented, demonstrating possibilities of wireless micro-systems on human body.**

Keywords—**Body energy harvesting, Energy scavenging, WSN, Embedded operating systems, Smart energy.**

INTRODUCTION

ENERGY harvesting is an important area on electronic systems. Everyday, electronic systems are greater and they have higher energy necessities, this problem is being studied today and there are several researches on this area. Next years computer systems and networks will continue increasing their computing power and will continue being miniaturized in order to be use by human beings in their daily life. This new approach for electronic devices goes to change human being's life. To this happens, it is necessary to find a sustainable energy source for these devices. This article shows the latest research about energy sources available from human body, new proposals and successfully examples about it.

Another interesting area is energy store, which covers, mainly batteries. On this area are considered capacitors, super capacitors and hybrid capacitors. Hybrid capacitors are most promising topic nowadays, they similar to lithium ion batteries, except for their charge storage. Hybrid capacitors store charge at the surface of the electrodes whereas lithium ion batteries store charge within the electrodes. Energy density on capacitors is higher than batteries and it is interesting to study the possibilities in a wireless micro-system.

STATE OF ART

Body energy harvesting can be classified in several ways. Nowadays there are several main areas where researches are focused. Here, there is a main classification related with source of energy. The main categories covered here are:

- Chemical energy
- Mechanical energy
- Thermal energy
- Radiation

Under these categories, there are classifications depending of where is scavenge this energy.

Chemical energy

Food is the main energy source of human bodies. It has nearly the same gravimetric energy density as gasoline and 100 times greater than batteries [1]. Human bodies store energy in fat cells distributed in various regions. Each fat gram stores and equivalent of 37.7 KJ. An average person of 68 kg (150 lbs) with 15% body fat stores an approximate equivalent of 384 Mega Joules [2]. Fat cannot be directly consumed by body cells. Fat molecules are long chains of glucose molecules. These are cut into single molecules and injected into the bloodstream. Glucose is the main source of energy for the brain and a basis for smaller molecules like ATP. One glucose molecule stores an energy equivalent of 16 KJ. In the human body, it can be converted into two ATP molecules in anaerobic respiration and into 32 ATP molecules in aerobic respiration. The ATP is then usable for muscle contraction. Both enzymatic breakdown processes require two ATP molecules for processing. In aerobic respiration, a glucose molecule is much more profitable than in its anaerobic form. The total quantity of ATP in the human body is about 0.2 mole, providing roughly the same amount of energy as a AA battery [3]. At any given time, the total amount of ATP and ADP is fairly constant and recycled continuously. Within 24 hours, all cells in the human body consume about 100 to 150 moles of ATP, which is around 50 to 75 kg [4].

Mechanical energy

Muscles in the human body convert food into mechanical work at efficiencies up to 25%. The usable mechanical output of human bodies can reach 100W for average persons and 200 W for elite athletes [1]. A 68kg man walking at 3.5 mph (2 steps/ second) uses 1.1 MJ per hour or 324 W of power. The raw physical energy required to lift the heel through 5 cm during the walk is only 67 W. Obviously only a small portion of these 67 W can be detoured to power an electric device without disturbing the human gait. According to *Starner and Paradiso*, a maximum of 13W is available for energy harvesting for a 1 cm stroke [2].

When mechanical energy is referred, it is necessary to consider several transduction methods. Between these methods it is possible to find: electrostatic generators, EAP or Electro Active Polymers, inertial systems and electromagnetic generators.

- *Electrostatic generators:*

Electrostatic transduction, which is both impractical and inefficient for large machines, becomes much more practical at small size scales and is well suited to micro-electromechanical (MEMS) implementation. Piezoelectric transduction is generally impractical for rotating systems but is well suited to the reciprocating nature of the motions typically used for harvesting (e.g., vibration). In electrostatic generators, mechanical forces are employed to do work against the attraction of oppositely charged parts; in effect, such devices are mechanically variable capacitors whose plates are separated by the movement of the source. They have two fundamental modes of operation: switched and continuous [5]. Mechanical work is done against the fringing field. There is an increase in stored electrical energy because the electric field strength increases with the reduction in plate overlap, and the energy density of the field increases faster than its volume decreases.

On the other hand, the piezoelectric effect is a phenomenon whereby a strain in a material produces an electric field in that material, and conversely an applied electric field produces a mechanical strain [6]. The former can be used to realize micro-generators. When an external force is applied, some of the mechanical work done is stored as elastic strain energy, and some in the electric field associated with the induced polarization of the material. Accordingly, *MIT Media Lab* team led by *Paradiso* developed a somewhat more modest piezoelectric insole. The stave was a 10-cm long, 16-layer bimorph, with eight 28 μm PVDF sheets laminated on either side of a 1 mm neutral plastic insert, that fit into a men's US size 11 and 1/2 shoe (see Fig 1). The actual device was seen to produce peak powers into a matched resistive load of roughly 15 mW at heel up and slightly less at toe off; over the course of a 1 step/second per leg standard walk, the average power was 1.3 mW.

Fig. 1: Dielectric Elastomers build into a heel of a show

- *Electro-active polymers:*

EAPs, these are similar to electrostatic generators, it is necessary to maintain a constant voltage to change on the electrodes. For a dielectric elastomer generator is necessary a relatively high voltage, between 1 and 6 KV for operation [7]. It will be also necessary lot of switches between low and high voltage, but we will gain a better strain properties. Those ones give us more energy per compression and, for extension, more power generation.

Usually they are made of silicone rubber or soft acrylics, trying always to have flexible materials, and they are extremely compliant. They have a similar performance as piezoelectric materials when accumulate enough strain, but in these devices it is easy to drive a 50-100% area strain. Like electrostatic mechanisms, these designs require a very high potential to be applied across the dielectric. Current is produced as the material is compressed and its capacitance changes, this is the same process that variable capacitor follows. However, they can produce higher voltage and are more versatile, thus they have excellent properties allowing much strain energy to be stored for power generation.

- *Inertial systems:*

Inertial systems and micro-systems can be attached at various positions on the human body. Positions exposed to higher accelerations will generate more power. The best mounting position is at the wrist. Today self-winding wrist watches use a 2 gram mass mounted off-center on a spindle. Inertial micro-systems generate more power when moved cyclic.

Despesse et al [8] researches analyses a structure for electrostatic transduction with high electrical damping. This electrostatic transduction is designed to operate with low frequencies, typically less than 100 Hz. The structure used, was an in-plane gap with a charge-constrained cycle. In the proposed scenario, the electrostatic force is linearly proportional to the inertial mass displacement in the same way. This allows two forces to be balanced for all displacements of the inertial mass. If the electrical stiffness is close to mechanical stiffness is achieved a high electrical damping. *Beeby et al* [9] explain how an 18 cm^2 ×1 cm volume device with a 0.104 kg inertial mass was electro discharge machined from tungsten and produced a scavenged power of 1052 μW for a vibration amplitude of 90 μm at 50 Hz. This represents a scavenged efficiency of 60% with the losses being accounted for by charge/discharge losses and transduction losses. A similar geometry silicon micro-structure of volume 81 $mm^2 \times 0.4$ mm with a 2×10^{-3} Kg inertial mass excited by a vibration amplitude of 95 μm at 50 Hz is predicted to produce a scavenged power of 70 μW. Inertial Microsystems can be attached at various positions on the human body. Positions exposed to higher accelerations will generate more power. The best mounting position is at the wrist.

- *Electromagnetic generators:*

Compared with electrostatic generators, electromagnetic generators are heavier and more difficult to tailor and require rotary movements. But magnetic machines running at sufficient speed can provide much higher efficiencies.

Some motions of human body are rotary, though not fully 360 degrees, and the speed of motions is cyclic and relatively slow. Other motions, such as heel strike, are distinctly linear requiring a linear machine or some mechanical converter to use a rotary machine. The best position to harvest power from cyclic movement on the human body is the wrist. The wrist moves faster than any other part of the human body. Power can be harvested whenever the user is walking.

Though this seems unpromising for magnetic machines, the rotation speed can be increased using flywheel arrangements in rotary motions. For linear motions, a mechanical spring can give high bursts of speed by releasing stored energy. The machine speed is not limited for the 1 Hz walking as some have proposed [10]. Better than 90% efficiency is routinely obtained in good machines with sufficiently high speed. An important disadvantage of magnetic methods is that the material is relatively heavy compared to other methods. Several problems exist with such energy systems. They tend to be big and heavy. Their power output is proportional to the scale of coils or length of stroke. Rotary magnetic power generators have a long tradition in the history of electrical generators. A wide variety of spring/mass configurations can be used with various types of material that are well-suited and proven in cyclically stressed applications. Comparatively high output current levels are achievable at the expense of low voltages. These systems, however, are quite difficult to build because the number of turns on planar coils is limited and because the magnet/coil velocity is restricted.

Another option in electromagnetic generators approach is linear motors, these motors are able to convert linear motion directly into electrical energy. A linear motor consists of sets of coils and magnets arranged on a line [11]. Induction is based on Faraday's law about the variation in magnetic flux. When the magnetic flux changes, a current is induced in the inductor. Traditionally, conductors are shaped like a coil. An output current is generated when either the relative movement of the magnet and coil, or when the magnetic field changes.

Low transduction efficiency yet high power output due to cumbersome mounting and bulk scale has been described in many applications [12]. Their power generation ability is characterized by direct proportion to the scale of coils or length of stroke. However, new designs outperform their predecessors several times.

Thermal energy

The human body produces waste heat in the range from 81W (sleeping) up to 1630 W (sprinting). During sitting, a mere of 116 W is available [2].

Carnot efficiency limits the amount of power that can be harvested. Harvesting thermal energy always requires a temperature difference. The bigger the difference the more energy can be harvested. Assuming normal body temperature of 37° C, the Carnot efficiency is 5.5 % for 20° C (difference of 17 ° K) and 3.2 % for 27° C (difference of 10 ° K) room temperature. Using a Carnot heat engine to model the recoverable energy yields 3.7 – 6.4 W of power. Carnot efficiency defines a theoretical upper limit to the efficiency of every thermoelectric generator. Todays standard thermo piles provide 0.2 % – 0.8 % for temperature differences of 5 – 20 ° K [13]. A design of a micro machined thermopile from 2007 shows output voltage of 13 $mV/K/cm^2$. Simulations showed an output power around 1.5 μW at 1V for a watch sized TEG placed on a human body. For a temperature difference of 10° K, an output voltage of 130 mV was measured [14].

Another design uses the commercially available *Peltier* element PKE128A1030 with an attached heat sink as shown in Fig 2. The TEG setup generated 2.05 mW at 334 mV for 6.71° K temperature difference and 4.97 mW at 530 mV for 11.36° K [15].

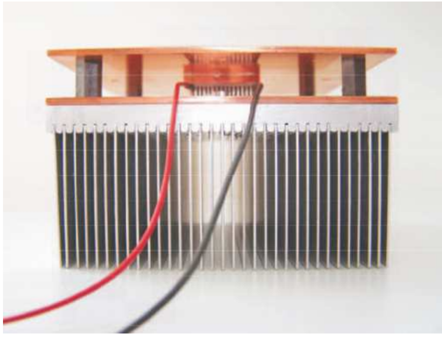

Fig. 2: TEG with attached heat sink

Incoming Radiation

Human bodies are constantly receiving energy in form of radiation of different wavelengths. Sunlight is just one small spectrum of incoming radiation. One design uses a wireless energy transmission. This technique offers the possibility to send energy from one point to another. A well-known technology that uses this design is RFID [16], which derives their energy inductively, capacitively, or radiatively from a tag reader. Most RFID chips talk back to the reader changing their impedance or reflection coefficient. These chips are low power devices on the consumption range of 1-100 μW, depending of their configuration. Several examples from today are keyless access systems, sensors [17], interfaces [18], crystal bulk resonators [19] or new proposals like blood pressure monitors [20].

There is another options to use energy from environmental radiation, the use of solar cells could be another possibility. This system involves several factors such as chemistry of the batteries, power management features of the system and the own characteristics from solar cells. Solar energy harvesting through photo-voltaic conversion technique provides up to 15 mW/cm3 of power [21]. This energy includes the electromagnetic spectrum form infrared to ultraviolet light.

Indoor power density typically ranges from 100 $\mu W/cm^2$ to 1000 $\mu W/cm^2$, and outdoors can be up to 100 mW/cm2. Solar cells efficiency can be up to more than 30% [22]. Power densities are similar for indoor solar cells, around 0.017 mW/cm^2, and batteries. On the other hand, outdoor solar cells provide around 1.42 mW/cm^2, this is more than 80 times more power [23].

PROPOSAL

This article proposes to use a multi-scavenge system to acquire energy from human body. It expects to scavenge enough energy to supply a WSN micro-system, which has the capacity to read sensors and send this information via wireless network.

In this proposal will be used a wireless system-on-chip (SoC) from STMicroelectronics. This SoC (model STM32W108) has a consumption of 93 mW in transmit mode (+3 dBm) with ARM core running at 24 MHz, 79.5 mW in reception mode with ARM core running at 24 MHz and a consumption of 13.5 mW in sleep mode. It will test a WSN based on *EnOcean* and another one compliable with *IEEE 802.15.4*. In order to test, several network protocols are considered. Candidates are *EnOcean, ZigBee, 6LoWPAN* and *DARP*. These protocols make use of different energy saving techniques and it is interesting to find the protocol with less consumption and better performance between these ones. Finally, several energy harvesting and scavenging techniques will be applied, focusing on energy from incoming radiation, mechanical and thermal. With the combination of these different techniques it expects to obtain enough power to supply one node on the body.

Radiation scavenge energy method for wireless transmission systems permits to scavenge energy using a dipole antenna and an impedance on the receiver side. The received signal is rectified and mixed down to a lower frequency. Signals in a frequency range between 500 MHz and 10 GHz from different electromagnetic sources has been led in practice and failed to produce any useful results, because the signal strength of DVB-T, *Wi-Fi* or mobile network is very high and disturb other smaller signals for that hereby Energy harvesting could operate. A different situation exists when a transmission signal whose energy is to be used for the comparison supply of an embedded system, is itself produced. One example is a wireless system from *PowerCast* company. The wireless sensor nodes work at 915 MHz frequency and they are put to the power harvester boards that work with a *P2110* receiver, which supplies them with energy. The chip constitutes *P2110* received RF energy into a DC voltage, which is stored in a capacitor on the board, so that the supply of the sensor node is made possible [24]. The P2110 Receiver (see Fig. 3) converts signals in 850-950 MHz at a DC voltage. This practical example demonstrates with facts the applicability of these techniques.

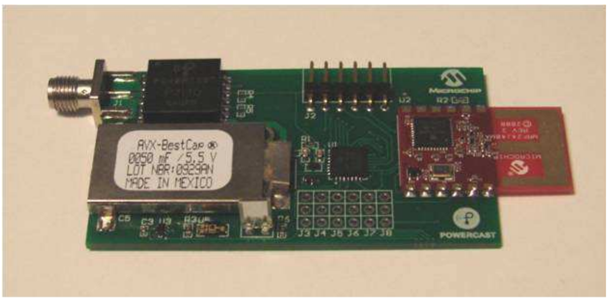

Fig. 3: PowerCast P2110 Module

The hardware proposed here has higher energy requirements than *PowerCast* but this proposal considers to use another energy source like thermal generators in shank or foot instep positions, these techniques provide in experiments up to 11.52 μW [25]. Another useful technique is extract energy from human respiration, experiments have reported up to 0.4 W of energy available [2]. The last method considered here is to use a mechanical transduction system on feet. This kind of system can scavenge up to 13 W, like *Starner* and Paradiso have reported [2].

Our proposal is supported by several examples developed by different research teams around the world. Next chapter presents some of these practical examples showing the possibilities of applying these technologies.

EXAMPLES

It is possible to find a lot of examples about how to scavenge energy from the human body. Here are presented several interesting examples to demonstrate the applicability of our proposal. Examples are classified following the same categories than chapter 2.

Mechanical energy

The *MIT Media Lab* team developed a prototype of an insole. It uses a PVDF piezo-electric foil as a shoe insole as shown in Fig 4. Power is generated through mechanical bending of the sole.

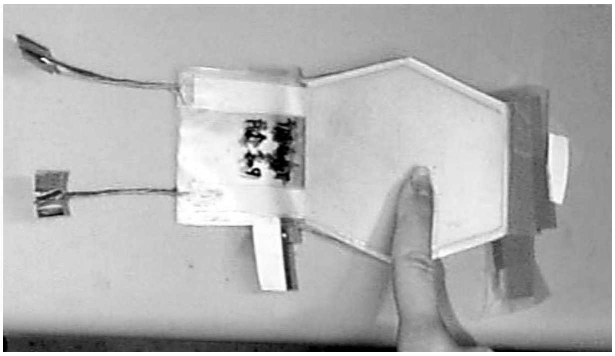

Fig. 4: Prototype PVDF bimorph generator

Their prototype is able to generate an average power of 1.3 mW at an optimum load resistance of 100 kOhm per shoe. The user weighted 52 kg and was walking at 1 Hz per leg. The team also produced another prototype that inserts a generator into the heel of a shoe. The generator was build of a flexible piezo-ceramic composite laminated on a curved piece of spring steel. The spring steel placed flat when the heel came down. The power generated by this design was measured as 60 mW peaks and 1.8 mW in average [2][26]. An improved design from *Shenck and Paradiso* uses two generators placed back-to-back. It generates power by the user's heel striking and flattening of the clamshell. To this prototype, the material used is an EAP [27], which is similar to piezo-electrics. In that material, mechanical stress produces a voltage which one is stored in capacitors. The latest studies confirm that polymers have more strains and are more versatile than piezoelectric. This design generates 8.4 mW of power in average [2][28].

There are other experiments using electrostatic generators that show how to use this technology on inertial systems. *Meninger et al* [29] simulated an in-plane overlap varying electrostatic generator based on a comb-driven structure and generated 8 μW from 2.5 kHz input motion. The limit to operate on the electrostatic generator is the high voltage produced. An integrated circuit was used and limited to the voltage of 8 V in this structure. It was necessary to charge and discharge the electrostatic generator at several points. In order to do this, *Meninger et al* used several feedback algorithms in addition to a measurement technique to take threshold and to choose the specific points to charge and discharge.

TABLE 1: AVERAGE GENERATED POWER AT DIFFERENT BODY POSITIONS [25]

Activity	Position	Average Power
Walking	Hip	1.40 μW
	Shank	10.30 μW
	Foot instep	11.52 μW
	Wrist	0.04 μW
Slow running	Hip	9.65 μW
Fast running	Hip	22.89 μW
	Shank	28.74 μW
	Foot instep	28.44 μW
	Wrist	4.36 μW
Jumping	Hip	22.70 μW
Cycling	Shank	0.36 μW
	Foot instep	1.34 μW
Knee rehab (sitting)	Shank	0.02 μW
	Foot instep	0.39 μW
Knee rehab (lying)	Shank	0.36 μW
	Foot instep	0.44 μW
Arm swinging	Wrist	3.08 μW
Arm trembling simulation	Wrist	0.62 μW

On the area of inertial systems there are several experiments to demonstrate the availability of these devices. Todays self-winding wrist watches use a 2 gram mass mounted off-center on a spindle. As the user walks around, the mass swings around the spindle and winds up the watch. Several electro-mechanical generators exist that fit into a watch [2]. The ETA Autoquartz Self-Winding Electric Watch generates 16 V at 6 mA in 50 ms pulses [30]. Another watch size generator is the Seiko AGS that creates 5 μW on average and 1mW if shaken hard [31].

A study from 2010 build a 50 g mass on a piezo-electric bender attached to an AC-DV converter electronics and tested it on various body positions. The measures of generated average power are shown in table 1.

Finally, in a scenario with permanent magnet generators, it is clear that they are most efficient at higher speeds and in a rotary arrangement, like wrist movements. *Kulah and Najafi* [32] focused on low frequency resonant structures but only measured 4 nW from a millimeter-scale mock-up with an efficiency less than 2%. For an excitation level provided, for example by finger typing, a device can generate 0.16 μW like Huang et al have demonstrated [33]. On a larger scale, *Amirtharajah et al* [34] described a moving coil electromagnetic generator contained in a low-power DSP application. The resonant frequency of the generator was 94 Hz, but the model of its performance predicted that an average of 400 μW could be generated from a 2 cm movement at 2 Hz in human-powered applications.

Thermal energy

Several thermal-to-electrical power generation approaches exist and many have been significantly enhanced by recent work in micro- and nanotechnology. For example, there are several reviews on the conversion efficiencies of the traditional thermoelectric elements. Recently, the conversion efficiency of an *InGaAs* monolithic interconnected module (MIM) using reflective spectral control thermo-photovoltaic (TPV) has been reported to be 23.6%, with a power density of 0.79 W/cm_2 [35], based on the amount of energy impinging on the cold surface (not in the entire control volume). Another novel energy conversion method, developed at Washington State University, integrates a fluid-vapor cycle with piezoelectric materials and thermal shunting techniques to create the P_3 power generator [36].

Incoming Radiation

Incoming radiation energy is composed by the energy from radio communications and solar energy. This energy includes electromagnetic spectrum form infrared to ultraviolet light. Solar cells efficiency can be up to more than 30% [37]. There is an interesting case that *Hande et al* [38] have presented. Indoor application for solar cells using fluorescent lights. This indoor light harvesting is aimed to power wireless sensor networks for biomedical sensing applications. A test bed using indoor lighting was presented for hospital use employing mono-crystalline solar panels. Mono-crystalline solar cells with typical efficiencies of less than 3% under indoor lighting conditions have a power density between

0.5 and 1 mW/cm^2, under light conditions of 1–5 W/m^2, which still surpasses other energy scavenger devices. Hande et al employed commercial mono-crystalline solar panels placed at 1 cm distance from overhead 34 W fluorescent lights. Two crossbow MICAz router nodes operating at a 50% duty cycle were powered by eight solar panels placed in short proximity to fluorescent lights, they tested satisfactorily for over 24h.

Another experiment was design from NASA Jet Propulsion Laboratory. This one uses a combination of a thermo-electric and solar panel called Power Tile [39]. The system is packaged in a less than 2 mm thick volume. The thermo-generator can scavenge some of the thermal energy incurred when solar radiation raises the temperature on the photovoltaic cell. It can also work as heat pump to keep batteries within a desired temperature range. The integrated circuit includes dc-dc converters, battery-charging circuit, thermo-electric heater driver and the required sense and control circuits. In full sunlight, the photovoltaic cell produces 125 mA at 2.1 V and the thermo-generator generates 20 mA at 0.8 V, when a temperature difference of 35 °C is present.

CONCLUSIONS

This article presents a state of art about energy sources from human body. These energy sources are classified in four main categories: chemical, mechanical, thermal and radiation.

This proposal presents a node based on a STM SoC with wireless communication capabilities. The power requirements oscillate between 13.5 mW and 93 mW. These requirements are not very different from other experiments made it before and it seems possible to supply a node in the wireless network, using only energy from human body. It was presented a combination of scavenge systems with an estimated energy potential of 13.4 W, enough to supply our wireless system.

It was also commented a wide range of examples from different energy sources. These examples permit us to present this proposal in order to obtain a completely functional wireless micro-system integrated on the human body.

FUTURE RESEARCH

Future researches are focused on develop a prototype and test the performance on a real scenario. It is also necessary to analyse which network protocol has more benefits to human body network environments.

Moreover, a second phase based on hybrid capacitors technology integration in order to store energy and use it when energy requirements are greater will be studied.

Finally other interesting way derivate of this work line is to study, which one is the best network technology that can be integrated on human body.

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