Energy Harvesting from Passive Human Power

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1 Abstract

Portable equipments are the first evolution from fixed equipments to make possible that some day computers are part of our everyday lives. The trends in technology allow the decrease in both size and power consumption of complex digital systems. This decrease in size and power gives rise to the concept of wearable devices in which digital systems are integrated in everyday personal belongings, like clothes, watch, glasses, etc. Power is a limiting factor in this kind of devices. Wearable computers are distributed devices in clothes and therefore the power must be distributed and supplied over the body.

Most of the current portable products are powered by rechargeable (also called secondary) batteries and they will remain as the main source for this kind of consumer products. However, the disadvantage of batteries is the need to either replace or recharge them periodically. The replace of a primary battery (a battery to be employed only once, and then discharged) means that the portable product's user has to carry with another one while the recharge of a secondary battery means that the electrical network has to be accessible to the portable product's user. The mobility of the portable device is restricted by the duration of the battery.

Batteries present another great disadvantage; they represent an important percentage of the volume and weight of portable products. Moreover, the increasing number of battery-powered portable products is creating an important environmental impact. As the user carry wearable devices one possible power source is the user and another one is user's environment.

Environmental sources are solar power (outdoor or indoor), vibrational sources, RF transmissions,... Human power is defined by the human power research group of the Delft University of Technology as the use of human work for energy generation to power an electronic device. One possible division is to distinguish between active and passive harvesting energy method. The active powering of electronic devices takes place when the user of the electronic product has to do a specific work in order to power the product that otherwise the user would not have done. The passive powering of electronic devices takes places when the user doesn't have to do any task different to the normal tasks associated with the product. The energy is harvested from the user's everyday actions (walking, breathing, body heat, blood pressure, finger motion, ...). Once the power is harvested it must be stored and there are many possibilities (capacitors, rechargeable batteries, etc.)

The objectives presented are focused in passive human power: human motion and body heat.

2 Objectives

Advances in low power design open the possibility to harvest energy from the environment to power electronic circuits. The goal of the present thesis project is to investigate energy sources to power wearable devices from passive human activity (motion and heat). Electrical energy can be harvested from human motion employing different transducers: piezoelectric materials, variable capacitors, and inductive generators. Thermoelectric generators will be the way to extract electrical energy from the temperature difference between the human body and the environment. Other possibilities in this research area like extracting electrical energy from the temperature difference between the wearable device and the environment or the human body will be also object of study for the thesis. The differences between every human power source (heat, human walking, arm motion, etc.) gives as result as many sources as possible locations or movements of the human body. To select the appropriate source is equivalent to select the appropriate motion and location in the human body. Therefore, the first phase in the design of a harvested energy generator is to make a quantificatin of the acceleration and temperature of different parts of the body for different activities. The second phase consists in obtaining a software model of the generator from the data obtained in the first phase and the electrical circuit of the transducer. The third phase consists in the design of a converter and/or storage circuit that has to take into account the output signal of the generator and its impedance. A final step of redesign may be necessary in order to adequate the simulations made in the second phase and the real results obtained by a prototype.

The output voltage and current of the generators is transient and discontinuous in nature, and must be converted to a DC signal. Therefore, a switching converter circuit is necessary. The switches will be activated by a control circuit but at initial moment the voltage obtained at the output is not enough to supply the switching circuit and it is necessary a starter circuit. Therefore, the circuit converter will work in two different modes. Mode 1 enters when the circuit is started-up or when the voltage level of stored energy is too low to feed the control circuit. When the output voltage has a sufficient level, it starts the efficient conversion, Mode 2. Therefore, Mode 1 is a storage circuit. The storage circuit is the previous step necessary to the design of the converter circuit. A study of the voltage level and time necessary to reach a certain voltage is necessary for the storage circuit in order to analyze is validity. This analysis is also necessary in order to determine if the converter circuit efficiency is greater than the storage circuit efficiency.

The specific partial goals to be achieved are:

- Power consumption of portable and wearable devices and evolution of rechargeable batteries.
    1. Bibliographic research of power consumption of portable and wearable devices and estimation of their consumption with the technology.
    2. Bibliographic research of the evolution of the main characteristics (gravimetric and volumetric energy density, recharge cycles, cost, ...) of secondary batteries.
- Human motion
    1. Acceleration map of the human body in movement for different human activities (walk, typing, bicycling,...) to get data of accelerations and frequencies of different activities that take place during a day in order to estimate the power that can be harvested.
    2. Piezoelectricity
        - Analysis of different mechanical structures (Theoretical and Experimental).

- Model of the piezoelectric generator (Theoretical and Experimental).
- Research on the conversion and storage of the electrical energy generated by the piezoelectric element (Theoretical and Experimental).
- Optimization of the system parameters in function of the human activity developed based on the data obtained from the acceleration map.

3. Electrostatic generator
   - Model of the electrostatic generator and evaluation of the most appropriate method of extraction of mechanical energy (Theoretical).
   - Research on the conversion and storage of the electrostatic energy (Theoretical and Experimental).
   - Optimization of the system parameters in function of the human activity developed based on the data obtained from the acceleration map.
4. Inductive generator
   - Model of the inductive generator and evaluation of the most appropriate method of extraction of mechanical energy (Theoretical).
   - Research on the conversion and storage of the electromagnetic energy (Theoretical and Experimental).
   - Optimization of the system parameters in function of the human activity developed based on the data obtained from the acceleration map.

- Body heat
  1. Human body model as a heat source (Theoretical and Experimental).
  2. Quantification of the heat source that can be extracted from human body without creating discomfort (Theoretical)
  3. Research on the conversion and storage of the thermoelectrical energy.

The acceleration map of the human body is necessary to take a model for the capacitive and inductive generator that will employ the human motion of a leg, an arm, etc. placing the generator in a knee, a wrist, a finger, etc. The most feasible location of the capacitive and inductive generators will be selected in function of the results obtained for the acceleration map. Once the response to the movement is well known, a capacitive and inductive generator model will be made employing as input source the data collected by accelerometers placed at different parts of the human body. HSPICE and Verilog-A will be employed to do the generator models. A realistic generator model is necessary in order to design successfully a converter and/or storage circuit. The piezoelectric generator will be placed in the insole of a shoe to harvest energy generated by human walking. Different mechanical structures must be analyzed in order to select the most appropriate one to obtain the maximum conversion efficiency. An accurate model of the piezoelectric generator, including the mechanical source, must be created in order to design an appropriate converter and/or storage circuit.

A human body model as a heat source is necessary to design a thermoelectric generator based on the difference between human body and environment in order to determine the quantity of heat that can be extracted without creating discomfort and the most appropriate location to place the thermogenerator. Once the thermal source will be well known, an optimal converter and/or storage circuit will be designed to convert heat into electricity.

3 State of the Art

Power is perhaps the most limiting factor in mobile technology. It restricts the autonomy, weight and size of portable devices.

Primary batteries compared to secondary batteries are relatively long lasting. However, a large-scale adoption would result in important environmental issues. Rechargeable batteries require that the user maintain them. Moreover, batteries sometimes are discharged when you more need the device and the access to the electrical network in order to recharge them is not always accessible even in urban environments.

Wearable devices and wireless sensor nodes are both areas where scavenge energy is an interesting alternative to batteries. Fixed computers have evolved to portable products. The next step is wearable computer. Starner [STA01a] establishes that wearable devices must be integrated with its user's daily life by embedding them into our clothing or by creating form factors that can be used like clothing (sunglasses). Wireless sensor nodes have power requirements as low as microwatts. Sensor nodes are often inaccessible and a change or recharge of batteries is difficult. The trends in technology allow the decrease in size, weight and power consumption of complex digital systems. However, batteries are still an important percentage of the mass and volume of digital systems. Wireless sensor nodes can harvest the energy from the environment while wearable peripherals can generate power from human actions or from the phenomena they sense.

The objectives of the Thesis Project are focused on passive human power. However, the previous work done related to environment energy sources is also include in this chapter since it includes interesting ideas that can be sometimes adapted to passive human power. The state of art is divided between environment energy sources and human sources although first some aspect about batteries are presented.

3.1 Batteries

The demand of primary and secondary batteries will rise in the following years due to the generation of energy-hungry portable devices like digital cameras, camera phones, PDAs,... If we focus on powering portable devices, lithium-ion are now the secondary batteries leader of the market and will be in future. The NiCd batteries market is shrinking and is being replacing by NiMH for environmental reasons. Alternative rechargeable batteries will make up less than 7% of all secondary batteries. Fuel cells are not going to play a significant role in secondary batteries market. Cost, size and performance are their main disadvantages [BAT].

Starner [STA04] reports on the slow pace with which battery's energy density has increased. The progression in mobile computing technology is represented in Figure 3. The y-axis is on a logarithmic scale. The value 1 in the graph corresponds to a mobile computer with the following characteristics: a 16 MHz 80386 with 8 MB RAM and 40 MB of hard drive space using a nickel-cadmium battery and communicating at 4800 baud. The processor is compared in terms of Intel's iCOMP index, the RAM and hard

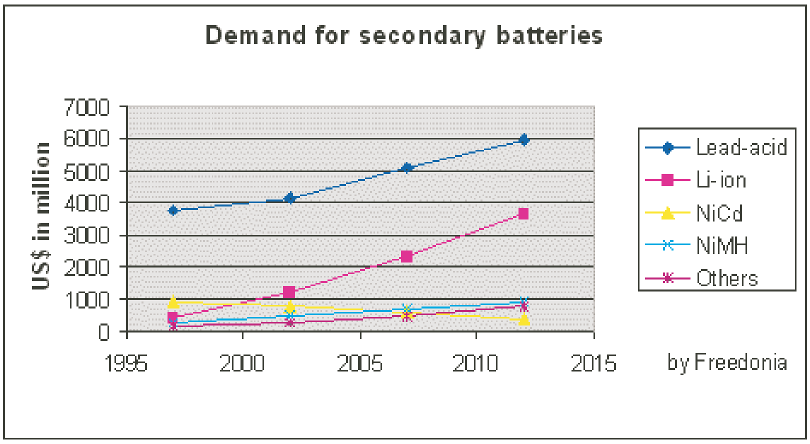

Figure 1: Demand of the most commonly used secondary batteries.

hard disk by size, wireless networks by maximum bits per second of data transfer, and battery energy density by the type of technology employed and the progression of these technologies in increasing the gravimetric energy density (J/kg). The battery energy density is the technology that less improves in mobile computing. In Figure 3 it can be shown that while disk storage density has increased over 1,200 times since 1990, battery's energy density has increased over 3 times. Batteries are a limiting factor to mobile device designers in terms of size, weight, and cost. Energy density is a measure

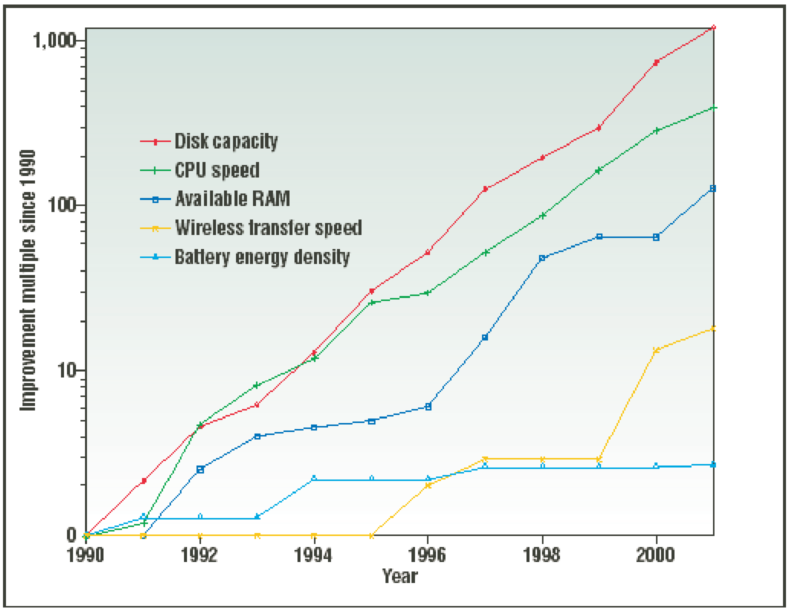

Figure 2: Improvements in laptop technology from 1990 to 2001.

of available energy in terms of weight and volume. Gravimetric Energy Density is calculated as:

$$\text{GravimetricEnergyDensity} = \frac{\text{capacityxaveragevoltage}}{\text{CellWeight}} \tag{1}$$

Volumetric Energy Density is calculated as:

$$\text{GravimetricEnergyDensity} = \frac{\text{capacityxaveragevoltage}}{\text{CellVolume}} \tag{2}$$

The first column of Table 1 classifies batteries between primary(non-rechargeable) batteries and secondary (rechargeable) batteries. The second column, power density, indicates how fast you can use it. The third column, energy density, is divided into volumetric and gravimetric energy density. The next four columns are related with temperature extremes. Self-discharge column shows the amount of energy lost while the battery is not used. It can be seen that self-discharge values for secondary batteries are greater than for primary batteries. Last column shows cycle life of batteries. Primary batteries can not be recharged, and therefore its life cycle is 1. The best characteristic in each column is highlighted.

		Energy Density		Temperature Extremes					
		by volume	*by weight*	Storage		Operation			
Chemistry	Power Density	**Wh/L**	**Wh/kg**	**Low**	**High**	**Low**	**High**	**Self-Discharge**	**Cycle Life**
Primary Batteries								***% per yr at 70F***	
Alkaline	Moderate	330	125	-40F	130F	-4F	130F	4%	1
Lithium Sulfur Dioxide	Moderate to high	415	*260*	***-65F***	***160F***	***-60F***	***160F***	**2%**	1
Lithium Manganese Dioxide	Moderate to high	*550*	230	-40F	140F	-4F	130F	**2%**	1
Zinc-Air	Low	***1050***	***340***	-40F	140F	-4F	130F	6%	1
Rechargeable Batteries								***% per mon at 70F***	
Lead Acid	High	70	35	-60F	130F	-40F	130F	20-30%	200
Vented Nickel Cadmium	High	90	37	**-65F**	140F	-40F	122F	10%	500
Sealed Nickel Cadmium	Moderate to high	80-105	30-35	**-65F**	113F	-40F	113F	15-20%	300
Nickel Metal Hydride	Moderate to high	175	50		113F	-4F	122F	20%	300
Lithium Ion	Moderate	200	90		130F	-4F	130F	5-10%	500

Table 1: Characteristics of batteries.

Figure 3 [JAN04b]shows a graph of energy density for different secondary batteries along time. The four main secondary batteries are shown in the figure: Nickel Cadmium (NiCd), Nickel Metal Hybride (NiMH), Lithium-Ion (Li-ion) and Lithium-Polymer (Li-polymer), in chronological order.Li-P have a gravimetric energy density greater than oldest rechargeable batteries like NiCd. In addition, the improvement rate is also greater for newest secondary batteries.

3.2 Environment Energy Sources

Ambient energy sources can be divided in vibration, solar power, RF, air flow sources, pressure variations, radioactive specks, ...Several approaches have been made during the last few years in order to harvest energy from the environment to power low power wireless sensor networks. These sensor networks are employed to improve the comfort

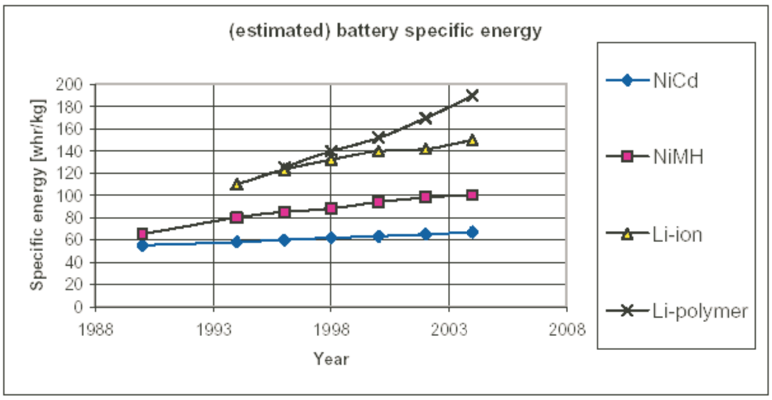

Figure 3: Specific energy of various types of secondary batteries, partly estimated.

and health of intelligent buildings. The energy needed by a wireless sensor is in the order of hundreds of micro watts. The main power sources studied for wireless sensor networks are solar power and mechanical vibration. Solar power technology employed for this application can be outdoor or indoor solar power. Figure 4 shows the power density available from solar cells, mechanical vibrations, and primary and secondary batteries as a function of time. The shaded boxes indicate the range of available power from solar and vibration sources. They are represented by boxes indicating the fact that the available power depends on the environmental conditions. The top of the box of solar power is for direct sunlight whereas the bottom of the box of solar power is for normal office lighting. Batteries are not a recommended power source for wireless sensors since the power source would limit the lifetime of the sensor [ROU03].

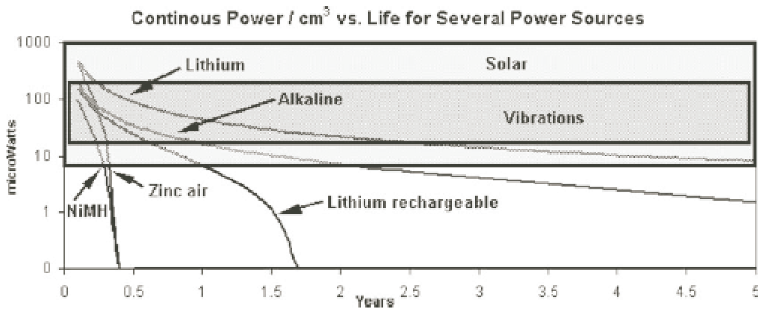

Figure 4: Power density ($\mu W/cm^3$) vs. lifetime for batteries, solar cell, and vibration based power.

3.2.1 Vibrating Sources

Roundy et al. [ROU03] have analyzed common vibration sources that occur in large commercial buildings, cars, trains, ... These sources produce low level vibrations that can generate 300 $\mu W/cm^3$. More energetic vibrations occurs in large industrial equipment but are not commonly available. A list of different measured sources characterized by its acceleration and frequency peak is available in [ROU03]. The measures were made with a standard piezoelectric accelerometer. Figure 5 shows the vibration spectra for an office window next to a busy street. It can be observed, as happens in all of the vibrations measured, that there is a peak magnitude at a low frequency with a few higher harmonics. The low frequency where the peak magnitude occurs is named fundamental vibration frequency. Most of the vibrations sources measured have its peak acceleration between 70 and 125 Hz. Another important characteristic that is common to the measured vibration sources is the fact that the acceleration spectrum is almost flat with frequency, which implies that the displacement spectrum falls as $1/\omega^2$. The analysis of vibration sources is a main point in the design of inertial micro-generators since the devices should be designed in order to resonate at the fundamental vibration frequency and it allows an estimation of the power generation can now be generated.

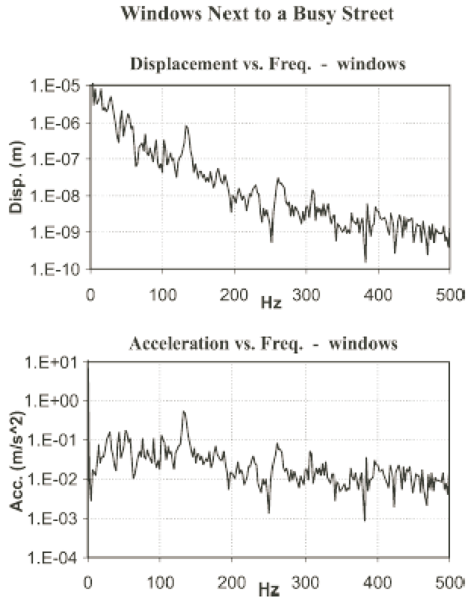

Figure 5: Vibration spectra for a microwave oven office window next to a busy street.

The vibration conversion presents a general model, an inertial generator, that is independent of the conversion mechanism. These generators consist of a proof mass suspended to a housing. When the housing is accelerated by a mechanical vibration, the mass moves relative to the housing and this available energy is extracted by the micro-generator. There are three possible types of devices in order to convert vibration energy into electrical energy: a variable capacitor (electrostatic fields), an electromagnetic inductor (electro-magnetic fields), and a piezoelectric transducer (straining a piezoelectric material). The advances in MEMS devices have made possible the design of autonomous sensors that harvest and store the environmental energy instead of using macroscopic power sources.

Table 2 summarizes the comparison between the three vibration converters. The first column corresponds to the energy density. The second column gives results for reasonable magnitudes applicable to each type of converter. The third column corresponds to energy density results with extremely high input values. Table 3 [ROU03] shows a comparison of the three vibration micro-generators that evaluates their advantages and disadvantages.

Type	Governing Equation	Practical Maximum	Theoretical Max.
Piezoelectric	$u = \sigma_y^2 k^2 / 2Y$	17.7 mJ/cm^3	335 mJ/cm^3
Electrostatic	$u = \frac{1}{2}\varepsilon E^2$	4 mJ/cm^3	44 mJ/cm^3
Electromagnetic	$u = B^2 / 2\mu_0$	4 mJ/cm^3	400 mJ/cm^3

Table 2: Summary of maximum energy density of three types of transducers.

Comparison of the relative merits of three primary types of converters

Mechanism	Advantages	Disadvantages
Piezoelectric	No voltage source needed Output voltage is 3–8 V	More difficult to integrate in microsystems
Electrostatic	Easier to integrate in microsystems	Separate voltage source needed Practical difficulties
Electro-magnetic	No voltage source needed	Output voltage is 0.1–0.2 V

Table 3: Summary of the comparison of the tree conversion mechanisms.

Electrostatic Generator

Meninger et. al. [MEN01] of MIT present an electrostatic generator that employs a variable micromachined capacitor. Two different designs are studied: a parallel capacitor operated with a constant charge and a comb capacitor operated with a constant voltage. These generators are also called Coulomb-damped resonant generators (CDRGs) based on electrostatic damping. If the charge on the capacitor is maintained constant while the capacitance decreases (reducing the overlap area of the plates or increasing the distance between them), the voltage will increase. If the voltage on the capacitor is maintained constant while the capacitance decreases, the charge will decrease. The mechanical energy converted into electrical energy is greater if the voltage across the capacitor is constrained than if the charge across the capacitor is constrained. However, the initial voltage source needed has a smaller value if the charge across the capacitor is constrained. A way to increase the electrical energy for the charge constrained method is add a capacitor in parallel with the MEMS capacitor. The disadvantage of this solution is that the initial voltage source has to increase its value. The energy is transduced through a variable capacitor and generates 8 μ W from a 2,520 Hz excitation input. The main disadvantage of this method is that a separated voltage source is needed in order to place an initial charge on the capacitor plates. The topology presented by Meninger et. al. is shown in Figure 6a). The dark areas are fixed by anchors to the substrate, while the light areas are free to move with inertial vibrations. Roundy et al. [ROU02a] [ROU03] names this topology as an in-plane overlap converter since the capacitance variation is produced by the changing in the overlap area of the interdigitated fingers. When the plate moves in the direction of the arrows, the capacitance changes as a consequence of the overlap area of the interdigitated fingers.

Sterken from the IMEC, Belgium, [STE02] have developed a new approach to electrostatic MEMS CDRG. The main improvement is the fact that an electret is employed for polarization so any voltage source is needed as in Reference [MEN01] micro-generator occurred. The device consists of two micromachined capacitors connected in parallel and carried with a constant charge. The variable capacitors have opposite capacitance variations. Roundy et al. [ROU02b] and Meninger [MEN01] et al. studies have time periods where no electrostatic conversion takes place since the variable capacitor has to be charged and discharged once the energy stored increases. However, the working principle of the variable capacitor presented in this paper ensures a duty cycle of 100%. The designed micro-generator prototype is capable to produce 100 μW electrical power at 1,200 Hz for a displacement of 20 μm.

Miyazaki et al. of Hitachi Ltd. [MIY03] have made a new approach to the electrostatic generator. This paper analyzes the efficiency of the electrostatic generator. The efficiency is the result of (1) the mechanical to electrical conversion of the variable capacitor, (2) the charge transportation from the variable capacitor to the LC tank circuit, and (3) the timing capture. The mechanical to electrical conversion has a power-maximizing condition that determines the optimum design of the micro-generator. The charge transportation efficiency is analyzed as a function of the energy consumption in inductance L, capacitance C, and parasitic resistance R. The timing-capture efficiency is assumed to be 100%. The mechanical to electrical conversion efficiency was 57% and the charge transportation efficiency was 37%, and so the total converter efficiency was 21%. The measured power of the micro-generator was 120 nW for an input vibration of 1 μm at 45 Hz.

Roundy et al. [ROU02b] from UC Berkeley designed a MEMS CDRG. The device works with a constant charge. Three different topologies are presented for micromachined variable capacitors. The first one corresponds to the one presented in Figure 6a) and is called in-plane overlap type. The second one, shown in Figure 6b), is named as an in-plane gap closing type since the capacitance changes by changing gap between fingers when the plate moves in the direction of the arrows. The last one, shown in Figure 6c), is named as an out-of-plane gap closing type since it oscillates out of the plane of the wafer. In this case the capacitance changes by changing gap between two large plates. Roundy et al. propose the electrostatic converter shown in Figure 7a) for the charge constrained conversion. V_{in} represents the initial voltage needed to charge with a fixed charge the variable capacitor, C_v, fabricated with MEMS technology.

Inductive Generator

Electromagnetic generator can be realized in two different ways that employs the same principle. A moving magnet whose flux is linked with a fixed coil or a fixed magnet whose flux is linked with a moving coil. The first configuration is preferred to the second one because the electrical wires are fixed. Williams et al. [WIL95]-[WIL01] of University of Sheffield fabricated an electromagnetic MEMS VDRG. A mm scale demonstrator, development of an electromagnetic micro-generator, generates 0.3 μ W from a 4 MHz excitation input.

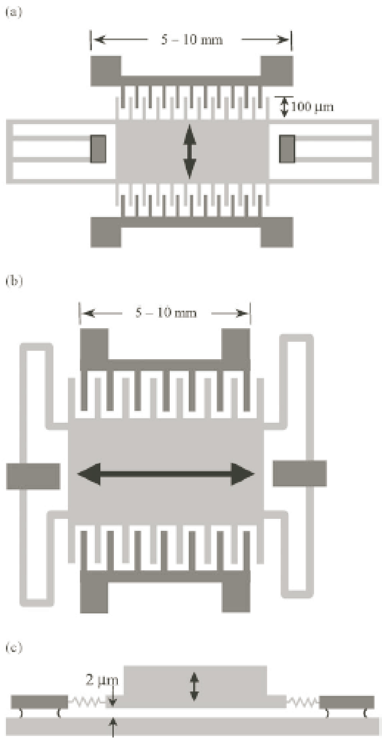

Figure 6: Three possible topologies for micromachined electrostatic converters.

Li et. al. [LI00] from the University of Hong Kong have fabricated an electromagnetic MEMS VDRG with a volume of 1 cm^3. The micro-generator generates 10 μ W power at 2 V DC with 64 Hz input frequency and 1000 μm input vibration amplitude. Another electromagnetic MEMS VDRG was fabricated for the same research group [CHI00]. This second micro-generator is a PCB-integrated generator that produces 5 μW power with an input mechanical excitation frequency of 104 Hz and amplitude of 190 μm.

Chandrakasan et al. [AMI97]designed with an electromagnetic VDRG built using discrete components which generates a power on the order of 400 μW using human walking as a vibrational power source.

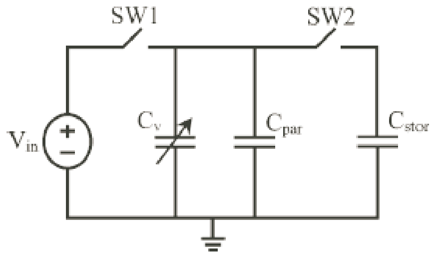

Figure 7: Circuit for the electrostatic converter.

Piezoelectric Generator

Piezoelectric materials are materials that are physically deformed in the presence of an electric field or that produce an electrical charge when they are mechanically deformed. Piezoelectric converters combine most of the advantages of both inductive and electrostatic generators. However, piezoelectric converters are difficult to implement on micromachined processes.

S. Roundy [ROU04] analyzed and fabricated a bimorph PZT generator with a steel center shim. The cantilever structure has an attached mass. The volume of the total structure is 1 cm^3. A model of the developed piezoelectric generator was made and validated. For an input vibration of 2.25 m/s^2 at about 120 Hz, power from 125 μW to 975 μW were generating depending of the load. The power recovered was analyzed connecting the generator directly to a resistive load or to a capacitive load. After this first effort, a DC-DC converter was designed and the generator supplied power to a low power transceiver. The radio transmits at 1.9 GHz and consumes 10 mA at 1.2 V and the vibration source was 2.25 m/s^2 at 60 Hz.

3.2.2 Solar Power

Solar energy is an environment energy available to power portable devices. A photovoltaic system generates electricity by the conversion of the sun's energy into electricity. Photovoltaic systems are found from the Megawatt to the milliwatt range producing electricity for a wide range of applications: from wristwatch to grid-connected PV systems. The application of photovoltaics in portable products could be a valid option under the appropriate circumstances.

In outdoors, the solar radiation is the energy source of the PV system. Solar radiation varies over the earth's surface due to the weather conditions and the location (longitude and latitude). For each location exists an optimum inclination angle and orientation of the PV solar cells in order to obtain the maximum radiation over the surface of the solar cell. Yearly irradiance is for example 992 kWh/m^2 in The Netherlands and 2026 kWh/m^2 in Tanzania. However, indoor irradiance is smaller, around 3.5 to 20 W/m^2. Nowadays, the majority of solar cells is made from semi-conductor materials: crystalline silicon (89%), amorphous silicon (10%), cadmium telluride (0.5%), copper indium, diselenide and gallium arsenide citesol:reinders. The power conversion efficiency of a PV solar cell is defined as the ratio between the solar cell output power and the solar power (irradiance) impinging the solar cell surface. For a solar cell of 100 cm^2, 1 W can be generated, if the solar irradiation is 1000 W/m^2 and the efficiency of the solar cell is 10%. The PV solar cells have a life time around 20 years.

Consumer products are often mobile or portable with a very low power demand, 1 mW, and a lifetime in the order of 2-5 years. The market of PV powered consumer products is dominated by amorphous silicon since it has reasonable efficiency levels in indoor environments. For outdoor consumer products, crystalline silicon is the option selected. Examples of consumer products that contains PV solar cells are: calculators, wristwatches, radios, headphones, laptops, cellular phones, solar lanterns, battery chargers, etc. In 1997, 6.5% of world PV cell shipments, the equivalent to 8.3 MWp, were destined to indoor consumer products citesol:reinders. In 1998 a number equivalent to 32.5 MWp have been sold for use in consumer products which represents about 19% of the market of PV cells [VEE03].

Veefking presented an interesting work about industrial design and PV power [VEE03] that takes into account an energy balance of different consumer products to ensure that solar energy is a valid source. In this paper it is presented the Solar Tergo, a charger for small portable products such as mobile telephones and MP3 players for use in combination with a backpack. The Solar Tergo consists of PV cells an a cell battery pack. Veefkind and Flipsen [VEE04] presented two experiments that are based on the Solar Tergo and that are carried out in order to obtain data on the energy that can be harvested by a PV cells incorporated on portable devices. The first experiment takes place with a stationary installation of equivalent cells to the Solar Tergo cells, an inclination of 70 oriented to the south. The second experiment takes place while biking in a urban environment in the Netherlands with an inclination about 90 of the Solar Tergo. The paper compares the output of PV cells on portable device with the output of a stationary PV cell.

Solar energy is also a valid power source for pacemakers, and other implants and biosensors. Actual devices use lithium based batteries that power during a limited period, three years, the devices. The Instituto de Energía Solar from Unviersidad Politécnica de Madrid and the Grupo de Dispositivos Semiconductores from Universitat Politécnica de Catalunya have designed a system to power this class of devices with solar energy. The system consists on an optical fiber with the same diameter that a hair that is placed under the skin in an accessible situation by the sun like the hand. The optical fiber goes to the the implant in which it is placed a PV cell [BEN04].

A new technology of solar cells is been developing. Until now, solar power has required expensive silicon-based panels that produce electricity four to ten times more costly than conventional power plants. The new technology of solar cells provides cheap and flexible solar cells. General Electric, Konarka technologies, Nanosolar, Siemens and STMicroelectronics are working in the revolution in solar cells. Konarka is producing strips of flexible plastic that are converting the light into electricity. Konarka's films are cheap and easy to make, using a production line of coating machines and rollers. The new printable solar cells cost less than half the cost of conventional panels to obtain the same power. Their lightweight and flexible properties make them appropriate for allocating them into all sort of surfaces: laptops, cell phones, ... Moreover, it could cover buildings or cars to recharge the batteries of hybrid cars. Konaka will start to sell its solar films during 2005. Advances materials science, including nanomaterials, is the base of printable solar cells. Siemens predicts that in a short period of time their printable solar cells will have an efficiency of 10%. Nanosolar is developing the idea of spraying nano solar cells onto almost any surface. This technology could enable Nanosolar to spray-paint photovoltaics onto building tiles, vehicles,... and wire them up to electrodes. Nanosolar predicts that by the end of 2005 will have prototypes that capture 10% of incoming solar energy [FAI04].

3.2.3 Radioactive Specks

A new power source for portable devices is presented by Lal and Blanchard [LAL04]. First of all they present the need of a smaller and longer-lasting power sources that present batteries to power MEMS. The Cornell University and the University of Wisconsin have been working in harvesting the energy released naturally by tiny bits of radioactive materials. All the particles have been spontaneously emitted by radioactive materials. The device designed is called nuclear micro-battery. This new power source is a more solid effort than microfuel cells. Microfuel cells have relatively low energy density, about 5-10 times that lithium-ion batteries, need to keep replenishing the fuel and eliminating byproducts and the packaging to contain fuel is difficult to scale down. The efficiency of nuclear micro-batteries is about 4% but could produce 50 mW of electric power with 10 mg of polonium-210, contained in 1 cm^3, during four mounts (the half-life of polonium-210 is 138 days). Nowadays, a new project has started to boost the efficiency to 20%. These new units named as radioactive piezoelectric generators, the radioactive source is 4 mm^2 thin film of nickel-63. On top of it, a rectangular cantilever is placed. When electrons fly spontaneously form the radioactive source to the copper sheet , the cantilever is charged negatively whereas the is charged positively. Then, the source attracts the cantilever. The top of the cantilever has piezoelectric material so the mechanical stress of the bend produces a voltage across the electrodes attached. When the cantilever bends to the point where the cooper sheet touches the radioactive source, electrons flow back to the source and the electrostatic attraction finishes. At this moment, the cantilever oscillates and produces a series of electric pulses. Another idea presented in the paper that is not exclusive from these authors is to give its own battery, in this case nuclear battery, to each component (sensor, actuator, microprocessor). In this way, even if a main battery is necessary to power some components it could be smaller if multiple nuclear microbatteries could run the rest of devices.

3.2.4 RF Power

A rectenna is a rectifying antenna that is employed in order to directly convert microwave energy into electrical energy (DC electricity). A rectenna can be constructed from a schottky diode located between antenna dipoles. The diode rectifies the current induced in the antenna by the microwaves.

The RF radiation can be an interesting way of distributing power to embedded electronics. This solution works well if there is a source very near to the electronic device that will employ the energy. However, law regulations limit the power radiated to a values that allows to receive a power around 50 μW transmissions for a transmission of 5 meters.

3.3 Human Power

Electronic systems that harvest energy from the environment require to be located close to the source (an ambient radiation source, a vibrating source, a solar source, etc.). Another available source that is in permanent contact with mobile and wearable computers is the user. So, human body can be considered as a storehouse of energy. There exist two possibilities: power can be scavenged from the user's everyday actions or can be intentionally generated by the user. Arjen J. Jansen [JAN04b] uses the term human power as short for human powered energy systems in consumer products. Different ways to provide energy from the product's users to the product are given by the research group: work from force exerted by body parts, variation in temperature, blood flow and chemical reactions. The main objective of the Personal Energy System (PES) research group of the Delft University of Technology is the conversion of energy from muscular work exerted by humans into electricity. Moreover, the muscular work exerted is made as active power instead of passive power in most of research done.

Starner [STA96] also presents human power as possible source for wearable computers. He analyzes power generation from breathing, body heat, blood transport, arm motion, typing, and walking.

Activity	*Kilocal/hr*	*Watts*
sleeping	70	81
lying quietly	80	93
sitting	100	116
standing at ease	110	128
conversation	110	128
eating meal	110	128
strolling	140	163
driving car	140	163
playing violin or piano	140	163
housekeeping	150	175
carpentry	230	268
hiking, 4 mph	350	407
swimming	500	582
mountain climbing	600	698
long distance run	900	1,048
sprinting	1,400	1,630

Table 4: Human energy expenditures for selected activities.

Table 4 [STA04] provides the power dissipated by the human body during several activities. The option to parasitically harvest energy from the everyday human activity implies that an unobtrusive technique has to be adopted. Figure 8 [STA04] shows a summary of possible power recovery from human body sources and the power generated by each action in parenthesis.

3.3.1 Power from Pedaling

The access to Internet via bicycle-powered computer and a Wi-Fi network from a Laos Village is presented in [APP03]. The computer is an ultra-efficient Linux PC that sends signals via a wireless connection to a solar-powered relay station. The PC power is supplied by a car battery charged by a person pedaling a stationary bike. 1 minute of pedaling generates about 5 minutes of power.

Windstream Power Systems Incorporated has been designing and manufacturing independent power systems making use of renewable energies for thirty years. Windstream offers human power generators. The Human Power Generator MkIII, HPG MkIII, can be pedaled or cranked by hand and it can generate an average continuous power about 125 W by pedaling and 50 W by hand-cranking. The Bike Power Module consists on a generator, bearings, and frictional wheel all mounted on a steel bracket in order to generate 100-300 W [WIN].

Nissho has manufactured Aladdinpower and also a stepcharger that is powered by the movement of the feet and can generate up to 6 W [KUI03] [STA04]. Freeplay [FRE]

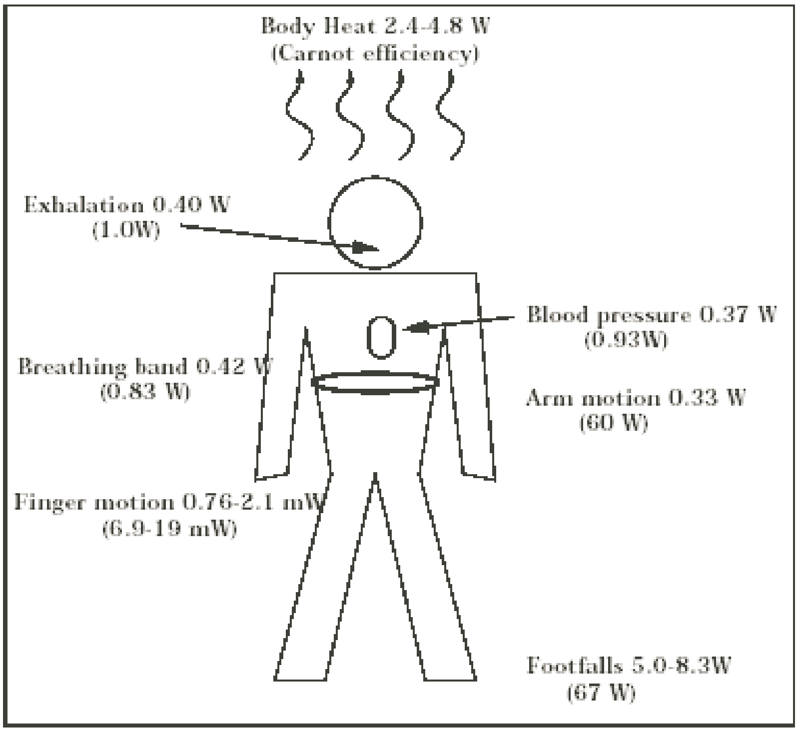

Figure 8: Power for body-driven sources;total power for each is included in parentheses.

has also developed a similar product called Freecharge Portable Marine Power that can be also powered by solar and wind energy.

30 seconds		1 hour music on a discman
4 minutes	of	running a watch for life
20 minutes	cycling	Charging a cell phone
7 hours	equals	one workday of energizing a 60 W light bulb
7 hours		4 hours of computer use

Table 5: Relation between energy expenditure of cycling and energy consumption of some consumer products.

In [KAZ04] appears the idea of an energy fitness club where people could reload their portable device while getting in shape and estimate that 10 minutes pedaling on a bicycle could generate 2 W, and therefore reload a mobile phone.Table 5 gives a relation between the energy generated when pedaling a bike and the energy consumption of some consumer products. A more specific idea is the cell phone charge by the bicycle via a click-on device mounted on the steer of the bicycle and that employees the electricity from the dynamo in order to charge the cellular phone. Last year, Orange, a GSM network provider, launched the Orange beach cruiser, a bike with a dynamo that is used to charge a cell phone mounted on the steer [ORA].

3.3.2 Power from Walking

Walking is one of the usual human activities that have associated more energy [STA96] [STA96] [MOL00]. Piezoelectric materials, dielectric elastomers and rotatory generators have been employed in order to harvest energy from human walking activity by the MIT Media Laboratory.

Piezoelectric Shoe Inserts

The piezoelectric effect was discovered by Jacques and Pierre Curie in 1880. Curie's brothers found that certain materials subjected to mechanical strain, suffered an electrical polarization that was proportional to the applied strain. The Curies also discovered that these material when were exposed to an electric field, suffered a mechanical deformation. This effect is known as the inverse piezoelectric effect.

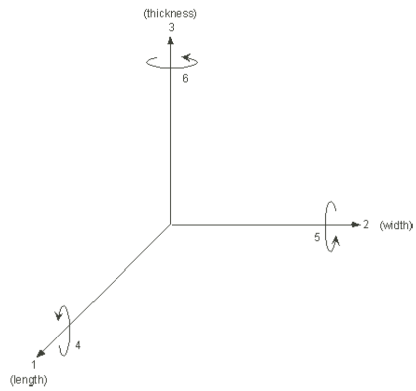

Figure 9: Piezoelectric axis.

Figuire 9 shows the 6 directions of the axes, three cartesian directions plus the shear around the three axes, that are presented in the piezoelectric effect. Electrical parameters are in the X, Y and Z directions whereas mechanical parameters includes also the shear about the three axes. The direction of polarization for piezoelectric materials is usually direction 3. Piezoelectric materials are generally employed in mode 33 or in mode 31. In mode 33 the mechanical stress is applied in direction 3 and the electrical field takes place also in the direction3. In mode 31 the mechanical stress is applied in direction 1 whereas the electrical field is obtained in direction 3.

The two most common types of piezoelectric materials are PVDF, polyvinylidene fluoride, and PZT, lead zirconate titanate. There exist three different ways to excite a piezoelectric material in order to generate electrical energy: compression, slapped and bent [DON00]. Table 6 [STA96] lists piezoelectric properties of PVDF and PZT.

The most efficient way to generate electrical energy from a piezoelectric material is the compression of a PZT in mode 33 d_{33}, piezo strain tensor. However, the elastic modulus of PZT is 4.9 x $10^{10} N/m^2$, it would take a significant force to compress the material sufficiently[starner 1996]. A PXE 5 piezo with dimensions 100 x 40 x 20 mm, where 100 is the thickness, generates 1.6 mJ for an input force around 1500 N [DON00].

Property	Units	PVDF	PZT
Density	g/cm^3	1.78	7.6
Relative permitivity	$\varepsilon/\varepsilon_0$	12	1700
Elastic modulus	10^{10}N/m	0.3	4.9
Piezoelectric constant	10^{-12}C/N	$d_{31}=20$ $d_{33}=30$	$d_{31}=180$ $d_{33}=360$
Coupling constant	CV/Nm	0.11	$k_{31}=0.35$ $k_{33}=0.69$

Table 6: Piezoelectric characteristics of PVDF and PZT.

To use a slapper mechanism in order to provide the adequate force to the piezoelectric material requires a very specific design. Nunaporov of the Russian Academy of Science uses a microhammer and a spring to obtain an electrical energy of 2.1 mJ from an input force of 29.4 N with a device that has dimensions 80 x 20 x 10 mm. A tank capacitor of 100 μF was charged with 6.5 V with the energy obtained [DON00].

	Mode 31	Mode 33
V$_o$	$g_{31}\frac{F_1}{W}$	$g_{33}\frac{F_3}{WL}H$
q	$d_{31}\frac{F_1 L}{H}$	$d_{33}F_3$

Table 7: Voltage, V$_o$, and charge, q, obtained in the plane perpendicular to direction 3 applying a mechanical stress in direction 1, mode 31, and in direction 3, mode 33. q is the piezo stress constant, d the piezo strain constant, F the force, L,H and W are the longitud, thickness and width of the piezoelectric film, respectively.

Properties and dimensions of PVDF make it appropriate for obtain a higher mechanical-to-electrical efficiency by bending. In a thin PVDF film the ratio L/H is on the order of 1000, while $d_{31} = 23x10^{-12}m/V$ and $d_{33} = 33x10^{-12}m/V$ [MSI]. If it is considered that $F_1 = F_3$, V$_o$ and q for the mode 31 will be on the order of 700 times greater than V$_o$ and q for the mode 33, as can be seen from Table 7 [MAT04a]. Therefore, for the same mechanical energy input, more electrical energy output is obtained in mode 31 than in mode 33 when PVDF piezoelectric films are employed. However, for PZT mode 33 is usually a better solution than mode 31 since thickness is a little greater than length and width of the piezoelectric material.

The MIT Media Lab has developed a full system that harvests parasitic power in shoes employing piezoelectric materials [SHE01]. The low-frequency piezoelectric shoe signals are converted into a continuous electrical energy source. The first system consists on harvesting the energy dissipated in bending the ball of the foot, placing a multilaminar PVDF bimorph under the insole. The second one consists on harvesting the foot strike energy by flattening curved, prestressed spring metal strips laminated with a semiflexible form of PZT under the heel. Both devices were excited under a 0.9 Hz walking activity. The PVDF stave obtained an average power of 1.3 mW in a 250 kΩ load whereas the PZT dimorph obtained an average power of 8.4 mW in a 500 kΩ load. Therefore, the electromechanical efficiency for the PVDF stave is 0.5% and for the dimorph is 20%.

The present paper present two electronic circuits to convert the electrical output of the piezoelectric element into a stable dc output voltage. The first circuit consists on a diode bridge connected to the piezoelectric element to rectify its output. The charge is transferred to a tank capacitor since the moment that the charge exceeds a voltage value. At that moment the tank capacitor is connected to a linear regulator that provides a stable output voltage. The second circuit substitutes the linear regulator for a high-frequency switching regulator in order to improve efficiency. Piezoelectric source for human walking activity has low frequency (approximately one cycle per second), high-voltage (hundred of volts), low-currents (on the order of 10^{-7} A), and low-duty-cycle current pulses. Therefore, a forward-switching power-conditioning system has been designed. The control and regulation circuitry is not activated until voltage across C_b, tank capacitor, exceeds a certain voltage value. There exists a start up circuit in order to accumulate charge on C_b while there is no enough charge to activate the switches of the circuit. Once the control circuit is activated, a peak detector activates the switch that charges C_b when the input signal reaches its maximum voltage and deactivates the switch when a low voltage is detected. The converter's electrical efficiency is 17.6% and the system is capable to provide electric power continuously during walking activity takes place.

Trevor Baylis is actually working also in an electric shoe capable of charging batteries to power cell phones, MP3 players, or any low power portable device harvesting the energy from walking. The prototype is described as a pair of desert boots with a couple of wires sticking out of the sole and a solar panel placed at the toe area to obtain more power. A piezoelectric crystal insole is placed in the heel of the boot. In January of 200, Trevor Baylis, John Monteith, and Barry James filed a patent for their electric-shoe idea. After that, they founded the Electrical Shoe Company (ESC) with Texon, a footwear fraternity that makes 11.2 billion shoe parts annually and supplies components to every major manufacturer [DRA01].

Two Baylis electric-shoe prototypes were tested in a trek across Namibia in 2000. One of the prototypes was a pair of piezoelectric-powered boots. After five days of walking, the piezoelectric boots charged half of an empty mobile telephone's battery and a call was made. ESC works with other designs to create a shoe generator but Baylis is convinced that the piezoelectric solution is the best one for its low-cost and high-return. Currently, ESC is developing a new piezo-based substance in order to improve present piezoelectric materials that generates very high voltages and low currents.

The first generation of ESC product will recharge spare batteries but the company would like to power directly low power devices via conductive clothing in a future. Therefore, the next step will require a regulator device.

Ottman et. al. presented a circuit with a piezoelectric element connected to a diode bridge with a tank capacitor wired to a switch-mode dc-dc converter. An analysis of the converter is realized in order to obtain the optimal duty cycle of the converter that maximizes the harvested power. The use of the system proposed increases the harvested power by 325 % as compared to when the battery is directly charged with the piezoelectric rectified source. In the analysis done the piezoelectric source is supposed to be a sinusoidal waveform. The switch-mode dc-dc converter is placed in order to control that voltage across the tank capacitor will be the optimum value to ensure that energy transferred from the piezoelectric element to the charging battery is maximum [OTT02] [OTT03].

Elastomer Heels

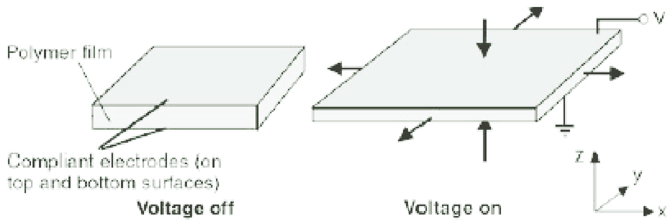

Figure 10: The dielectric elastomers actuate by means of electrostatic forces applied via compliant electrodes on the elastomer film.

Dielectric elastomers are electronic electroactive polymers (EAPs) that can produce electric power from human activity. The main development area of EAPs are artificial muscles since EAPs hold promise for becoming the artificial muscles of the future. Figure 10 [PEL00] show how the electrostatic forces due to the electrodes voltage difference squeeze and strech the film. Dielectric elastomers can grow by as much as 400% of their initial size. Electronic EAPs are driven by electric fields and require high voltages. SRI International is the most promising laboratory working in EAP. SRI International began work on artificial muscles in 1992. However, dielectric elastomers can produce electric power when work in generator mode. When a voltage is applied across the dielectric elastomer which is deformed by an external, the effective capacitance of the device changes and with the appropriate electronic circuits, electrical energy is generated. The energy density of these materials is high. DARPA and the U.S. Army funded the development of a heel-strike generator based on dielectric elastomers to power electronic devices in place of batteries. The device under development can produce 1 W of power during normal walking. The device is being developed to supply power to soldier but the technology is also applicable to civilian uses [ASH03] .

Rotatory Magnetic Generator

The Media MIT Laboratory also developed another technique for extracting energy from foot pressure: an electromagnetic generator. The electromagnetic generator is analyzed in [KYM98] and in [HAY00]. In the first referenced paper, Kymissis et al. analyzed an electromagnetic generator made by the Fascinations Corp. of Seattle that was mounted to the outside of a shoe. The first design obtained an average power of 0.23 W in a 10 Ω load, which matched its impedance, for a 3 cm stroke which interferes with walking. The second referenced paper presents an unobtrusive magnetic generator system integrated into common footwear. The average power obtained was 58.1 mW, with a peak power reaching 1.61 W, in a 47 Ω load. The width of the pulses is around 110 ms. The average power decrease with reference to the previous design is due to the fact that for close to 90% of the stride, no power is harvested by the generator.

The other Baylis electric-shoe prototype was a miniature dynamoelectric machine built into one of its hollowed-out heels. However, the dynamo's prototype broke after a few hours. Baylis believes that the piezoelectric solution is the best one for harvesting energy from walking [DRA01].

3.3.3 Power from Arm Motion

From 1990 to nowadays, the number of products that employ human power and more specifically arm motion is increasing. In 1992, Seiko introduced the Kinetic, a wrist watch powered by a micro generator that converts the motion of the watch while it is worn by its user into electrical energy stored in a capacitor. [Engineering a human powered mp3 player, Delft]. The idea wasn't new but Seiko improved the technology. The average power output generated when the watch is worn is 5 μW. However, when the watch is forcibly shaken, the power generated is 1 mW. After Seiko Kinetic, the Swatch Group launched another watch that is self-powered, the ETA Autoquartz Self-Winding Electric Watch [PAR00].

Trevor Baylis, an English inventor, cooked up a low cost radio, BayGen Freeplay, that worked on a hand crank. The BayGen Freeplay requires only a couple of human calories to work. If the user wind up to the hand crank during 30 seconds, the radio stores enough power in a fully wound-up spring to listen to the radio during 30 minutes [DRA01]. Freeplay continued to develop their radio adding a capacitor and later a rechargeable batteries and solar panels [KUI03].

Another portable radio powered by an alternative system is the Dynamo & Solar (D&S) radio, produced in China. It can be powered by batteries charged by a solar panel, by net-current or by a hand-powered dynamo. Winding the handle at a moderate speed (25 mA), it takes 11 hours to charge the battery while the solar panel can charge the battery with 0 - 5 mA in a cloudy day or with a maximum of 48 mA in a bright sunshine day [STE04].

Freeplay, the company that created the BayGen radio also has introduced another products powered by arm motion while has continued innovating in the radio market. The new Freeplay's radios have rechargeable batteries and solar panels. Freeplay has three different models of flashlight that transform the arm motion energy into electric energy via a wind-up mechanism. The flashlights produces 8 minutes of beam for 30 seconds of winding. A mobile phone charger is also available. It allows to the phone's user to do emergency calls employing a wind-up mechanism that provides 2-3 minutes of talk time, and several hours of standby) per 45 seconds of winding. All these products have a crank-driven alternator, power train components, a high capacity rechargeable battery, and power conditioning electronics. The alternator has a high efficiency, around 75% [FRE].

Another company that offers human powered products is Atkin Design and Development, AD&D. Their prototype Sony radio delivers 1.5 hours play time for a 60 second wind. Their Motorola phone charger prototype provides 2 hours standby and 10 minutes talk time for every 60 seconds wind. The Professional torch model shine for 15 minutes on a 60 second wind and can be used as attachable charger unit for the radio and phone [ATK].

The Nissho's Allandinpower is a hand-powered device that one cranks by squeezing. It produces 1.6 W of power when the handle is squeezed at 90 times per minute. The device is capable of provide energy to general applications like a phone or flashlight. One minute of powering gives one minute of talk time when a mobile phone is powered [KUI03] [STA04].

3.3.4 Power from Typing

Paradiso et al. [PAR01] presented a piezoelectric pushbutton to wirelessly transmit a digital identification code using the mechanical energy given by pushing a button without the need of batteries. The piezoelectric ceramic is used in resonant mode in order to obtain the highest efficiency of mechanical-to-electrical energy conversion. To ensure that the piezoelectric works in resonant mode, the piezoelectric receives an impact during a short time and then it is released. A piezoelectric generator produces high voltages at low currents whereas electronic circuits require low voltages at high currents, and therefore a step down transformer is employed. The transformer is employed also to match impedances between the piezoelectric and the tank capacitor. The tank capacitor will have the value required in order to don't selfdischarge before its storage energy would be used. The inductance of the transformer and the capacitance of the piezoelectric element form a resonant circuit that must be equal to the element's mechanical resonance in order to accomplish an optimum energy transfer. The tank capacitor power a linear regulator that supply a stable voltage to a digital ID encoder. The code generated is broadcasted via an RF transmitter. The piezo generator of the MIT Media Laboratory operates at 7% of efficiency and delivers 2 mJ of energy with every push of the button of 15 N.

Enocean, a spin-off of Siemens, has a commercial wireless remote control without batteries, PTM 100 and PTM 200. The force employed to push down the switch is used bending the cantilever piezoelectric ceramic at its extreme but without resonance. The block diagram of the radio transmitter module is similar to the device designed by the MIT Media Laboratory [ENO].

Lightning switch, a spin-off of Face International Corporation, produces also wireless and batteryless building control system. The transmitter converts the mechanical action of pushing the switch into electrical energy to send a RF signal to the receiver. The mechanical to electrical energy conversion is made by a piezoelectric device called Lightning that was developed by NASA and employed on the IIS (International Space Station) [FAC].

Energy generated typing a laptop is not enough to supply power continuously to the portable computer but can be employed to recharge the secondary battery. This device was patented by Compaq in the US in 1999. The device was invented by Adrian Crisan, a Compaq's engineer, and allows to reduce the size of batteries or make them last longer. Compaq has not offered a commercial laptop using this device until now. The recovery system consists on a keyboard power generator. Each key has one or more magnets attached to it and a coil surrounds each magnet. Therefore, each type a key is depressed, the magnets move over the coils and causes a current that goes to a charge pump which multiplies the voltage and provides energy to recharge the battery [STA04] [BEA99].

3.3.5 Power from Inertial Microsystems

Previous work done about harvesting energy from vibrational sources is focused on inertial micro-generators prototypes that are tested under laboratory conditions using artificial vibrational input signals with a frequency much higher than the associated to human activities. Lukowicz et al. [LUK02] estimates an output power from acceleration measures on nine points of human body while the subject under test is walking at 4 km/h, normal speed, on a treadmill. The sensors employed were three commercial sensor-modules: two ADXL210E and one ADXL202E tri-axial sensor-modules from Analog Devices Inc. The output power estimated is arround 200 μW for an oscillation amplitude of 5 mm.

Mitcheson et al. [MIT02] present a new class of micro-generator (CFPG). The paper classifies microgenerators as velocity-damped resonant generators (VDRGs) and Coulomb-damped resonant generators (CDRGs). The new class of microgenerator is called Coulomb-force parametric generator (CFPG). The CFPG does not operate in resonant manner as the previous one done. Mechanical resonance is useful when the vibration source amplitude is small compared to the allowable mass-to-frame displacement. However, when the the allowable mass-to-frame displacement is small compared to the vibration source amplitude the CFPG offers better results. Therefore, it can be the most appropriate micro-generator in order to harvest energy from human motion.

Chandrakasan also designed with Amirtharajah an electromagnetic VDRG built using discrete components which generates a power on the order of 400 μW using human walking as a vibrational power source [AMI98].

3.3.6 Power from Body Heat

Human body emits energy as heat. Therefore, heat can be harvested from human body to supply energy to portable devices. However, Carnot efficiency puts an upper limit on the heat energy that can be recovered. The temperature difference between the human body and the environment, e.g. low rom temperature (20 C) can be harvested. Starner [STA96] estimates that the Carnot efficiency with this temperature conditions is 5.5%. In a warmer environment the Carnot efficiency drops while in a colder environment the Carnot efficiency rises. The recoverable energy yields 3.7-6.4 W of power. However, evaporative heat loss account for 25% of the total heat dissipation, and therefore the maximum power available drops to 2.8-4.8 W. However, the previous calculus are assuming that all the heat radiated by the human body can be recovered and transformed into electrical power. Another problem is the location of the device dedicated to the capture of the heat of the human body. When the skin surface detects cold air, a rapid constriction of the blood vessels in the skin reduces the skin temperature to the temperature of the cold air. Therefore, the efficiency of the Carnot device will drop. The solution to this problem would be a wetsuit but nowadays is inadequate for some applications. Starner [STA96] recommend the neck as a good location to the Carnot engine since it is part of the *core* region, those parts of the body that always must be warm. Moreover, the neck is an accessible part of the body and the engine can be easily removed by the user without creating discomfort. Starner estimates that approximately a power of 0.2-0.32 W could be recovered by a neck brace. Starner and Maguire [STA98] [STA98] evaluated the possibility to dissipate heat of a mobile computing by thermally coupling it to he user. The interest of this paper for harvesting power from human body heat resides in the fact that offers a thermal human body model. Electronic applications and human body can not assume constant temperature reservoirs.A thermal human body model is necessary in order to know how much heat energy can be harvested from a part of the human body without disturb.

Thermoelectric generator

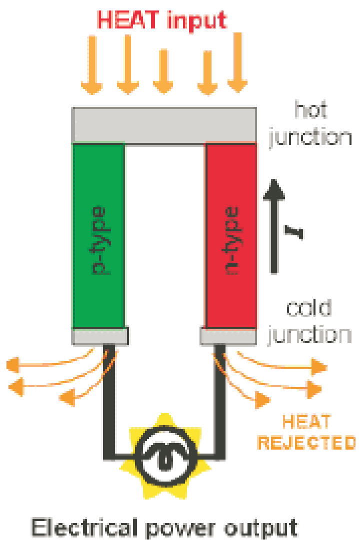

Figure 11: Thermoelectric generation.

Figure 11 [THE] illustrates the model of a thermoelectric generator. it consists of a thermocouple, comprising a p-type and n-type semiconductor connected electrically in series and thermally in parallel. The thermogenerator (based on the Seebeck effect) produces an electrical current proportional to the temperature gradient between the hot and cold junctions. An electric load is connected electrically in series with the thermogenerator creating an electric circuit. The Seebeck coefficient is positive for p-type materials and negative for n-type materials. The heat that enters or leaves a junction of a thermoelectric device has two reasons: 1) the presence of a temperature gradient at the junction 2) the absorption or liberation of energy due to the Peltier effect [ANG71].

Figure 12 [ANG71] illustrates a thermoelectric module. The module consists of pairs of p-type and n-type semiconductors forming thermocouples that are connected electrically in series and thermally in parallel. The output voltage obtained for N thermocouples is N times the voltage obtained for a single thermocouple whereas the current is the same as for a single couple [ANG71] [THE].

Applications

The Seiko Thermic watch uses a thermoelectric generator to convert heat from the wrist into electrical energy. It was the first watch to be powered by energy generated between the body and environment temperature. The watch was first produced in December 1998 in limited numbers, only 500 watches. Nowadays, the Seiko Thermic

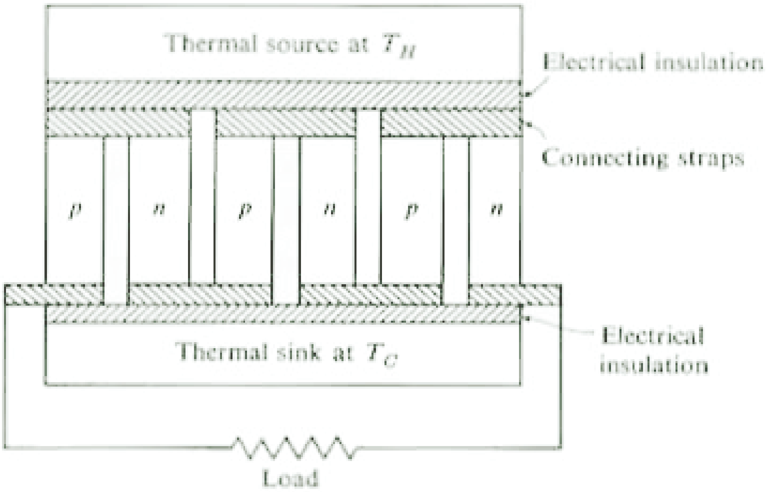

Figure 12: Thermoelectric module.

is no longer manufactured. The watch absorbs body heat through the back of the watch. The system consists on a thermoelectric generator converts the temperature difference into electricity to power the watch. The thermoelectric generator produces a power of 1.5 μW or more when the temperature difference is 1 °C-3 °C. A boosting and controlling circuit connects the thermoelectric generator to the titanium-based lithium-ion rechargeable battery of 1.5 V. The battery supplies power to the motors of the watch and the movement driver that controls them. Seiko Instruments Inc. developed the world's smallest π-type Peltier cooling element. It has a high performance (equal to conventional cooling devices) and is 25%-12.5% smaller [SEI].

Applied Digital Solutions, based in Florida, announced in October 2001 the development of a miniature thermoelectric generator that converts body heat flow into 1.5 V to run a watch, embedded medical devices,... In 2002, ADS has already commercialized the thermoelectric generater named as Thermo Life. Peter Zhou, the chief scientist of ADS, informed that Thermo Life has a surface of 0.5 cm^2 and that can generate 40 μW at 3 V with a 5 degree difference in temperature. The energy generated is stored in a NanoEnergy battery, a thin-film battery developed by Front Edge Technology. The Thermo Life power generator applications are varied: attachable medical devices, electronic wrist watches, self powered heat sensors, and mobile electronics [ADS].

Maximum power obtained by a thermoelectric generator is proportional to A/l where A is the cross-sectional area and l is the length of a p-n thermoelectric leg couple. The power density is inversely proportional to leg length. Specific power [W/cm^2] can be increased if the thermoelectric elements reduce its height while maintaining the aspect ratio of legs. Ryan et. al. predict a specific power around 0.5 W/cm^2 for a 10 K temperature gradient at room temperature with a figure of merit, ZT, equal to 0.9. Thermoelectric microconverters are expected to have an efficiency of 5-6% and provide milliwatts of power at several volts. Microconverters can be employed to convert rejected heat to electric power, providing electric power and passive cooling at the same time. Ryan et al. also expound that manipulating electrical and thermal transport on the nanoscale it is possible to improve conversion efficiency and ZT is predicted to increase by a factor of 2.5-3 near room temperature [RYA02].

Stordeur and Stark developed in 1997 a Low Power Thermoelectric Generator (LPTG) for the D.T.S. company. The LPTG of D.T.S. is a small compact thermoelectric generator whose output is compatible to the requirements of micro electronic and micro matched system loads. The working range of LPTG is near room temperature not higher than 120 °C. The LPTG provides a power output of 20 μ W and a voltage of about 4 V under load at ΔT = 20 K [STO97]. A new approach was presented two years after the previous work that is capable of converting 15 $\mu W/cm^2$ from a 10 K temperature gradient [STA99b].

Stevens [STE99]presented in 1999 a paper that describes a thermoelectric generator arranged to produce electric energy from the temperature difference that exists between air and ground temperature. The paper also presents a procedure for the design of the optimal thermogenerator. The relatively small temperature differences, around 10 K, cause a low efficiency of the device. Stevens summarizes the previous work made by Benson and Jayadev, Lemley, Wu, Chen, and Henderson on thermoelectric generators for temperature differences on the same range although the majority of the literature is focused on temperature differences one or two orders of magnitude greater.

Lawrence et. al. presented later a thermoelectric generator prototype that exploits the temperature difference between the air and the soil to generate a small quantity of electrical energy [LAW].

Some authors have been working recently in thermoelectric technology to generate electrical energy from the waste heat of microprocessors to drive a cooling fan. This approach allows to separate thermal solution of electronic equipment from battery power which is an attractive idea for portable applications. Suzuki and Yazawa et.al. proposed to use a TE module directly attached to the CPU. The high thermal resistance of the TE modules causes that the CPU becomes very hot at heat dissipations over 10 W. A new design in order to solve this problem is presented by Solbrekken et. al. [SOL04a]. The concept is based on the idea that by controlling the amount of heat flow that goes through the TE module, the junction temperature can be maintained at or below a specific value. The rest of the heat flow is shunted through an alternate path and dissipated. With this design it is possible to generate on the order of 100 mW of electrical power that is enough to drive a cooling fan [SOL04b].

4 Work Plan

	2003		2004							2005										2006											2007				
Month	F	M	M	A	M	J	J	S	O	F	M	A	M	J	J	S	O	N	D	J	F	M	A	M	J	J	S	O	N	D	J	F	M	A	M
Model of the piezoelectric generator																																			
Analysis of different mechanical structures																																			
Conversion/Storage circuit for the piezoelectric generator																																			
Optimization of the system parameters of the piezoelectric generator																																			
Acceleration map of the human body																																			
Model of the electrostatic generator																																			
Conversion/Storage circuit for the electrostatic generator																																			
Optimization of the system parameters of the electrostatic generator																																			
Human body model as a heat source																																			
Quantification of the heat that can be generated																																			
Conversion/Storage circuit for the thermoelectric generator																																			
Model of the inductive generator																																			
Conversion/Storage circuit for the inductive generator																																			
Optimization of the system parameters of the inductive generator																																			
Writing																																			

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