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Smart Wireless Sensors Integrated in Clothing: an Electrocardiography System in a Shirt Powered Using Human Body Heat

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Abstract: A wireless electrocardiography system is integrated in an office-style shirt. The device is powered by a thermoelectric generator that converts natural heat flow from the body into electrical power. The thermoelectric generator outperforms AA batteries of the same weight in about 1.5-2 years of using, depending on the time the shirt is worn per day. The system is composed of 17 small modules spread over the shirt. The module thickness does not exceed 6.5 mm for convenience of the wearer. Smart electronic module with extremely low power consumption provides excellent quality of a cardiogram and smart power management. The system sustains machine washing with a drying cycle at 1000 rpm and pressing. No other service is required for the entire service life of the shirt.
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Keywords: Electrocardiography, Wireless sensor, Thermoelectric generator, Energy scavenging, Clothing

1. Introduction

Battery-free wearable wireless devices can be powered by energy scavengers when using low-power radio and electronics [1, 2]. However, energy scavengers are not reliable power supplies: photovoltaic (PV) cells do not work at night while a thermoelectric generator (TEG) fails to provide enough power and voltage if the ambient temperature is too close to the human body temperature [3]. To avoid power shortages, the logical solution is to provide a rechargeable battery. Then the power can be stored in the battery and the device can be powered even during the shortage of power generated by the scavenger.

Powering the devices in a piece of clothing is furthermore complicated because the latter can stay in a wardrobe for weeks or months until its owner decides to wear it again. In this case, not the standby power consumption but the battery self-discharge limits the storage period. Furthermore, machine washing and pressing of garments are high-temperature processes that accelerate the battery self-discharge. In this work, the TEG and PV cells are used to demonstrate the possibility of a wearable device in a piece of clothing with unlimited service life. The system is primarily powered by using thermoelectric conversion of human body heat into electrical power. The PV cells however are used in a standby regime to compensate for the battery self-discharge during long periods of non-use.

2. Thermoelectric Generator

Energy scavenging in general, including thermoelectric conversion of the human body heat, provides varying power output depending on many factors. At certain moments, the power generation minimizes or stops. At such moments, an energy buffer with some stored energy should power the application until the power generation is restored. A supercapacitor used as an energy buffer helps to avoid the shortage of power for only very short periods, on the scale from milliseconds (e.g., for buffering radio transmission bursts) to minutes. As a result, the systems such as the ones reported in [1-3], have been designed to work at power consumption near the minimum of expected power generation to avoid power shortages. The excess energy, which was produced all the time and not consumed by electronics, was wasted. If however a secondary battery is used as the energy storage element [4], it can provide the required power for days or weeks even with no scavenged energy. Therefore, using the battery requires much less power production on average and the TEG can be effectively miniaturized to be more comfortable for its wearer. (In this work, the TEG thickness has been reduced).

The practical limit of power generation in a 15 mm-thick wearable device at 22° C is about 25 $\mu\text{W}/\text{cm}^2$ when using state-of-the-art thermoelectric materials [5]. The thinner the TEG the less power per unit area of human body it produces due to decreased temperature difference on the thermopile [6, 7]. Therefore, a thin TEG in a shirt should occupy larger area to produce the same power as obtained in watch-thick wearable devices. In this work, to make a 1 mW-TEG unobtrusive, but thin enough for its integration in a piece of clothing, it is divided into 14 modules for comfort of the user. Such modular approach simplifies fabricating a family of TEGs for different wearable devices in clothes. Indeed, the power required for a particular application can be obtained by integrating a different number of optimized TEG modules into a piece of clothing with no necessity to redesign them. The voltage can be varied, if necessary, by using thermopiles with the same thermal resistance, but with another lateral dimensions of the legs, i.e., with a different number of thermocouples. In the ECG shirt, the 3 cm \times 4 cm modules are 6.5 mm-thick, Fig. 1. Their thickness is similar to that of electronics and PV modules.

The TEG modules have been integrated into the front side of shirt, Fig. 2. They occupy less than 1.5 % of the total area of the shirt. In the office, the thermoelectric generator typically provides the power within the 0.8–1 mW range at about 1 V on the matched load at 23 °C at person's usual sedentary activity. On a person walking indoors, the power production increases up to about 3 mW due to forced convection. The TEG is neither cold nor obtrusive for the user. In winter, the outdoor pieces of clothing are being worn on top of shirts. However, as measured at about 10 °C outdoors on a person wearing a thick jacket, the power generation is by about 10–20 % better than indoors with no jacket.

The TEG designing has been performed accounting for the thermal properties of human body, which is the only way to optimize a wearable TEG [5, 8, 9]. The exact location of TEG modules on the human body and their quantity in the final design of the shirt has been defined only after measurements of the

human body characteristics in the office, i.e., the heat flow through the thermally matched TEG module, and the thermal resistance in a clothed subject [10].



Fig. 1. Thermoelectric module having a thickness of three Euro coins for integration in a piece of clothing.



Fig. 2. Electrocardiography shirt and some of its modules. The TEG modules are chameleon-like painted for invisibility. The only one of modules has a different color to give an idea about its size.

The open-circuit voltage produced by the TEG has been measured at different temperatures, Fig. 3a. The power P on the matched load with the resistance R_L can be obtained as:

$$P = V_{open}^2 / 4R_L, \quad (1)$$

which is shown in Fig. 3 b.

3. Electronics Module

Fig. 4 shows a block diagram of the electronic system. The thermo-electric generator is used as the main power supply. Its output is up-converted by a fully integrated DC/DC converter and used to charge a rechargeable 2-cell NiMH battery. A small amount of additional power (most useful in standby mode when the shirt is not being worn) is provided by the solar cells and is used to directly charge the battery through a simple rectification circuit.

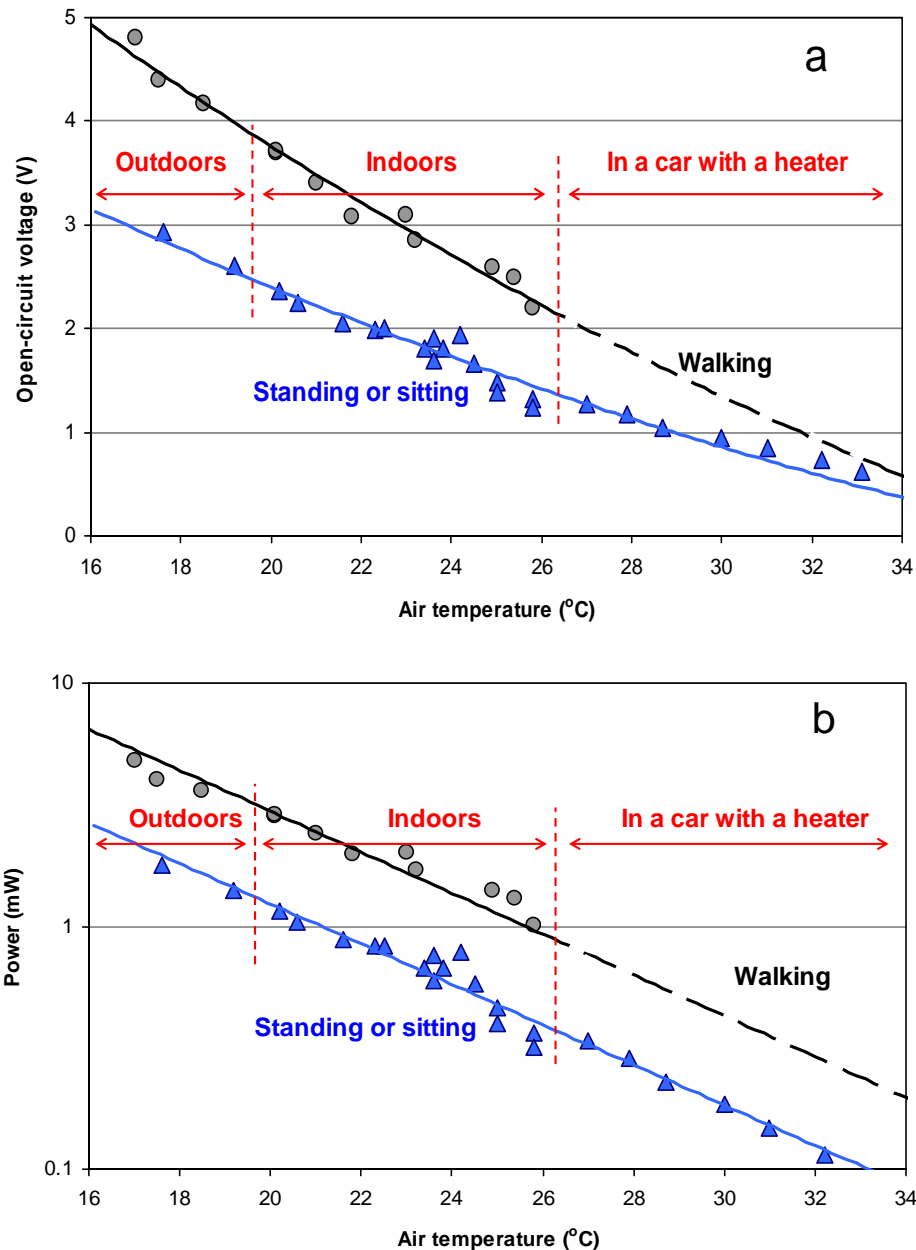


Fig. 3. Open-circuit voltage (a) and a power on the matched load (b) generated by a TEG at different temperatures. The two dependences correspond to natural convection (while standing or sitting) and forced convection (walking).

The battery (nominally 2.4 V) directly powers the system's low power microcontroller (MSP430F1611) and radio (Nordic nRF2401A). The electrocardiography (ECG) analog front-end electronics are powered from a 2.75 V supply which is provided by a 2nd stage of DC/DC conversion using a standard inductive DC/DC boost converter (MAX1723).

The fully integrated DC/DC up-converter [11] (Fig. 5) is fabricated in a 0.35 μm CMOS process. It works with an open-circuit voltage of 0.5 V or higher from a TEG. The converter's main block is the charge pump with a variable number of stages (1–7) and switching rate. The number of stages is controlled by the microcontroller for optimum conversion efficiency at a given input voltage. In this work, two converter chips have been connected in parallel for more efficient operation at the required power level of approx. 0.5 mW.

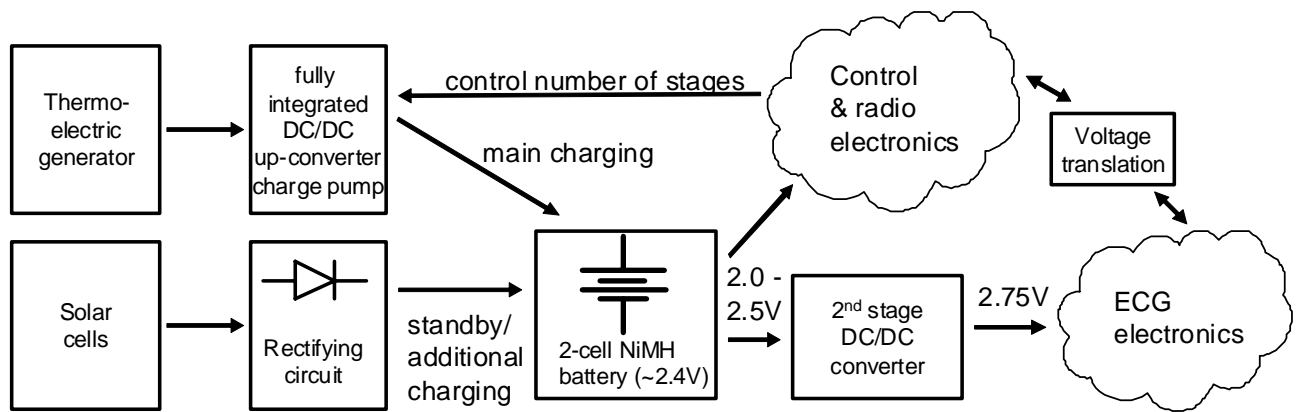


Fig. 4. Block diagram of the electronics module.

Fig. 6 shows the resulting conversion efficiency of the fully integrated DC/DC converter for the ECG shirt application. The maximum conversion efficiency measured for this application is 73 % for 6–7 stages at 0.5–0.6 V input. When matching losses and quiescent current (I_q) are included, the overall efficiency at an input open-circuit voltage of 2 V is 44 %. At higher ambient temperatures, i.e., when the generated power decreases, the conversion efficiency increases, e.g., at an input voltage of 1.2–1.4 V it reaches 50 %. Note that for the typical case in the ECG shirt application the open-circuit voltage exceeds 1 V, and the optimal number of stages as set by the microcontroller remains constant (four).

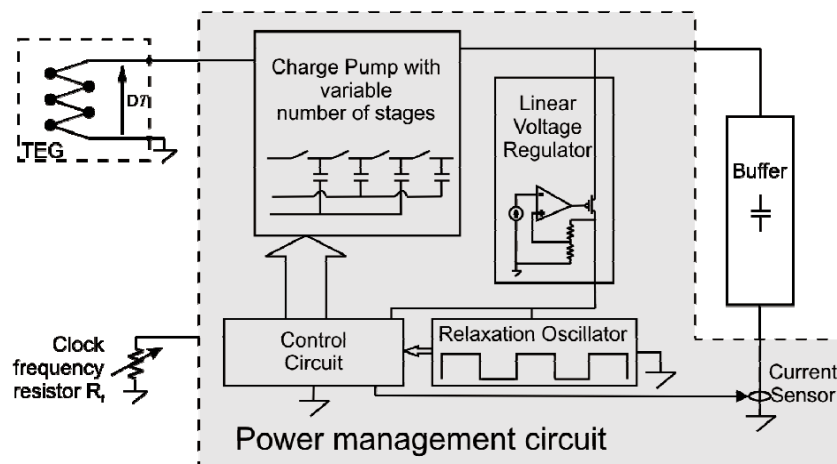


Fig. 5. Block diagram of the integrated DC/DC converter.

The limited efficiency of the fully integrated DC/DC converter when used for this application wastes a relatively large fraction of the available power. As an alternative solution, a variant of the system was produced that includes a discrete DC/DC conversion circuit similar to the one used in [1, 2]. In this circuit, the TEG charges a 1.2 V single-cell NiMH battery directly and the battery voltage is then up-converted to 2 V to power the control & radio electronics. The disadvantage of this discrete circuit, besides increased size due to the requirement for a relatively large inductor, is that it only functions well for open-circuit TEG voltages above 1.5 V. At lower voltages, mismatch causes most of the available power to be lost, and below 1.2 V no charging is possible at all (see Fig. 6). However, at 2 V open-circuit TEG voltage the discrete circuit achieves an overall efficiency of 75 %, which is significantly better than the fully integrated converter.

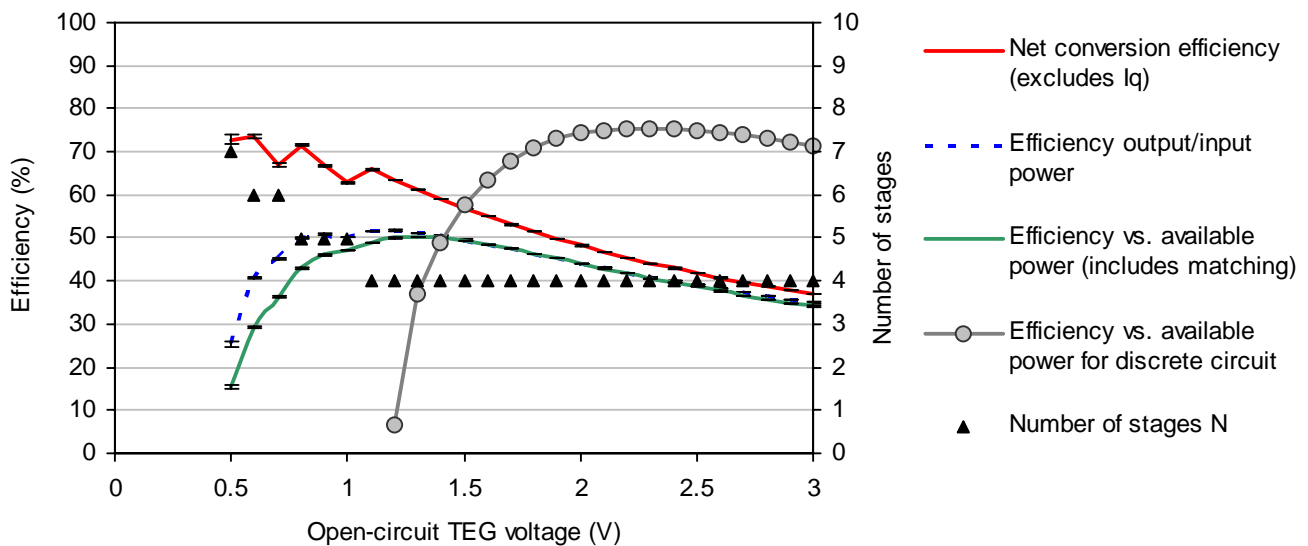


Fig. 6. Efficiency of integrated DC/DC converters and optimal number of stages. Efficiency for the discrete DC/DC conversion circuit is shown for comparison.

In parallel to the TEG power conversion circuit there is a secondary circuit that allows charging the battery directly from PV cells. Two PV cell modules with commercially available amorphous silicon solar cells of 2.5 cm × 4 cm size each are integrated in the shirt. This has two purposes: first, when the shirt is taken off and stored in an environment where light is available, the PV cells provide sufficient power to compensate for the self-discharge of the battery. A wardrobe with a window or a semi-transparent door is required. In this way, even after months of non-use, the electronics is kept in a standby state, ready to start operating by the moment the shirt is put on again. Second, it provides additional power during use, e.g., in the office, there is typically about 150–200 μW. Therefore, one could expect from PV cells about 50–100 μW averaged over 24 hours. (This amount depends on the person's lifestyle, but the worst-case lifestyle scenario of a patient must be accounted for.) The open-circuit output voltage of PV cells, e.g., 5.2 V in the office, is high enough therefore only a simple rectifier circuit is required.

In order to obtain high-quality ECG signals, an ultra-low-power low noise ASIC (60 nV/Hz^{1/2}) with an ac-coupled instrumentation amplifier is used [2, 12]. It consumes a power of 60 μW from a 2.75 V power supply. It is the only component that operates from the 2.75 V supply that requires another up-conversion step. This conversion step is 79 % efficient (including quiescent current). The amplifier rejects the common-mode signals coupled to human body, e.g., through interference from the mains, and also filters the differential DC voltage generated between two biopotential electrodes in order to prevent saturation of the circuit. It achieves a common mode rejection ratio (CMRR) of over 110 dB at a DC differential electrode offset of up to 50 mV. The amplifier has a high impedance (0.1 GΩ) that enables the use of conventional Ag/AgCl electrodes as well as certain types of dry electrodes, and minimizes the CMRR degradation under electrode impedance mismatch, i.e., if one of electrodes is not attached properly to the body.

The microcontroller receives the electrocardiography data from the preamplifier ASIC, digitizes it using its built-in 12-bit analog-to-digital converter, formats and compresses it. Then the data are transmitted to a PC using a radio transceiver in the 2.4 GHz band. A capacitor connected in parallel to the battery boosts the peak current capability during radio transmission bursts to minimize instability in the supply voltage.

The microcontroller also keeps track of the available input power and of the available energy stored in the battery. If these drop below a safe threshold, the system performs an auto-compensation by

temporarily reducing the sampling rate and transmission duty cycle by a factor of two. This allows a non-stop wireless acquisition of an ECG signal on cost of its quality even under severe energy deficit, where the full-quality signal acquisition cannot be maintained. If the available power from a TEG drops to quasi-zero, which happens when the shirt is taken off, or if the battery voltage becomes critically low, the system switches into a standby state. In this very low power standby regime, the system consumes less than 1 μ W. The battery self-discharge (typically 20–30% per month for NiMH batteries) dominates in this case. This does not create a problem if the shirt is not used for a month or two. However, for a longer period of non-use, the shirt must be stored in a place where the illumination could periodically reach PV cells. The user optionally can wake up the system from the standby state by pressing a wake up button. The same button also enables switching the system manually in the standby state if desired. If accidentally the battery is completely discharged, the shirt is still not lost. Its PV cells must be just placed in direct sunlight and charged in a course of several days. By using a wake up button, the operability of the system can then be verified. Once the battery reaches the minimum working voltage, the up-converter becomes functional and the ECG shirt can be worn again. During its daily use, the produced power typically exceeds the power consumption, so the battery will be fully charged in a course of several days.

Table 1 lists the power consumption of the full electronic system when acquiring and transmitting the ECG waveform at a normal sample rate of 256 Hz and at a reduced sample rate of 128 Hz.

Table 1. Power consumption of the ECG electronic system.

Sample rate	Circuit with fully integrated DC/DC converter (2.4 V battery supply)	Circuit with discrete components (2 V supply up-converted from 1.2 V battery)
Normal: 256 Hz	0.65 mW	0.50 mW
Reduced: 128 Hz	0.53 mW	0.44 mW

When the data from Table 1 are combined with the measured efficiencies in Fig. 3 and the average additional power generated by the solar cells (0.1 mW), as well as the output power of the TEG in function of temperature, the resulting autonomy of the system can be established. The system with the discrete components can autonomously function at full acquisition rate at average ambient temperatures up to 24 °C when the wearer is still or at up to 28 °C when he/she is walking. This DC/DC converter circuit continues operation (converting net power) until 28 °C (still) or 31 °C (walking). The system with the integrated DC/DC converter functions autonomously at full acquisition rate up to 19 °C (still) or 24 °C (walking) and at reduced acquisition rate up to 21 °C (still) or 26 °C (walking). This does not mean that the system will stop at an ambient temperature of, e.g., 35 °C. In such case, the battery will provide the power until the user enters the air-conditioned room. Furthermore, a temperature of 35 °C outdoors with a high probability means that there is a plenty of sunlight, so that PV cells instead of a TEG will be the main power supply for a while. The integrated DC/DC converter continues operation until 33–35 °C. The comparison of two types of up-converters corresponds to the observation that can be made in Fig. 3 that in the high voltage, high power range (as required for energy autonomy in the ECG shirt application) the discrete circuit is more efficient. In contrary, in the very low voltage, low power range (corresponding to higher ambient temperatures), the integrated DC/DC converter becomes more efficient.

4. Integration of the ECG System into a Shirt and its Performance Characteristics

The integration of ECG system modules into the shirt has been performed taking into account convenience for its wearer, typical direction of incident light and convenience of integration. Taking

into account that the ECG system is to be worn by persons having heart diseases, but not willing to demonstrate to others that they have such a disease, the radiators of TEG modules are colored like chameleon according to the shirt colors, Fig. 2. The wiring and electronics module of ECG system are located on the inner side of the shirt. The TEG units are located on a chest and proximal arm. Two PV units are placed on the shoulders to get maximum power. For minimizing sensation of cold due to aluminum hot plate of the TEG units touching the skin, the hot plates are only 0.5 mm-thick and have a minimal heat capacity. Therefore, after putting the shirt on, they immediately reach the skin temperature. Thermopiles act as a thermal isolation in the process of heat rejection from the body, i.e., similar to the cotton. Therefore, no sensation of cold is registered during the use of the shirt.

The shock protection is the most important aspect for a TEG because of extreme fragility of thermopiles. Using protection grids like in the wrist devices developed earlier [1, 3] has been rejected from the beginning because these significantly increase thickness and weight of the TEG modules. Instead, the shock protection components made of thermally isolating materials have been placed in between the radiator and the hot plate of the TEG modules. Before and after final integration into the shirt, all units successfully passed laundry with a drying cycle at 1000 rpm. The corresponding acceleration was 250 g. The necessity of laundry caused implementing reliable waterproof encapsulation of all the modules. Despite the fact that a non-iron type shirt has been used in this work, its pressing is performed on a regular basis.

The electronics module is integrated in a two-sided flex circuit, Fig. 7. The circuit is divided into quasi-rigid islands with dense components alternated with empty flexible zones. This gives a limited amount of flexibility to the circuit and makes it compatible with embedding in clothes and with laundry (very high accelerations). The batteries at the bottom of the circuit also serve as placeholders to keep the substrate a minimum distance of about 2 mm away from the skin. This improves the antenna performance characteristics as compared to direct contact of the module with the skin. The complete electronics module is made waterproof by using silicone molding, which makes it machine-washable.

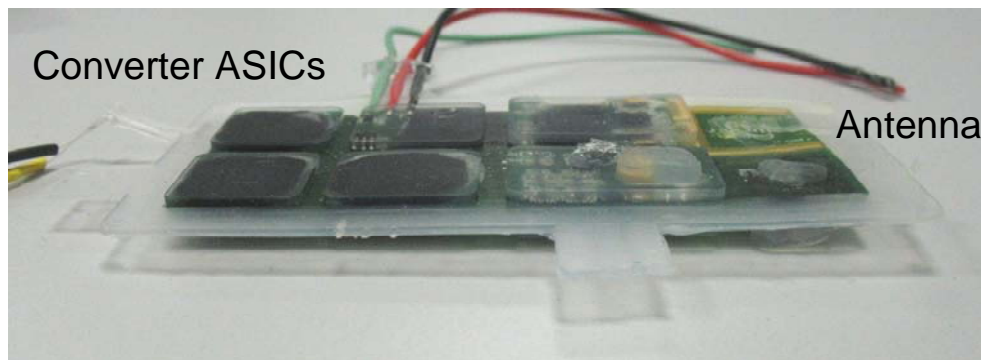


Fig. 7. Encapsulated flexible electronics module.

The examples of recorded electrocardiogram are shown in Fig. 8 for the cases of standard regime of operation and energy-saving regime with halved data transmission rate, to which the system switches in case of severe energy deficit.

5. Conclusions

The evolution of body-powered devices during five years of their development indicates that the only low-power applications, i.e., below 1–2 mW, can be powered using human body heat unobtrusively,

on one hand. This means that practically none of medical devices existing on the market can be self-powered. On the other hand, it has been shown that most of wireless health monitoring and medical devices can work at such power level with no loss in a signal quality. Further miniaturizing energy scavengers can be done in case of electronics with less power consumption and with lower-power radio.

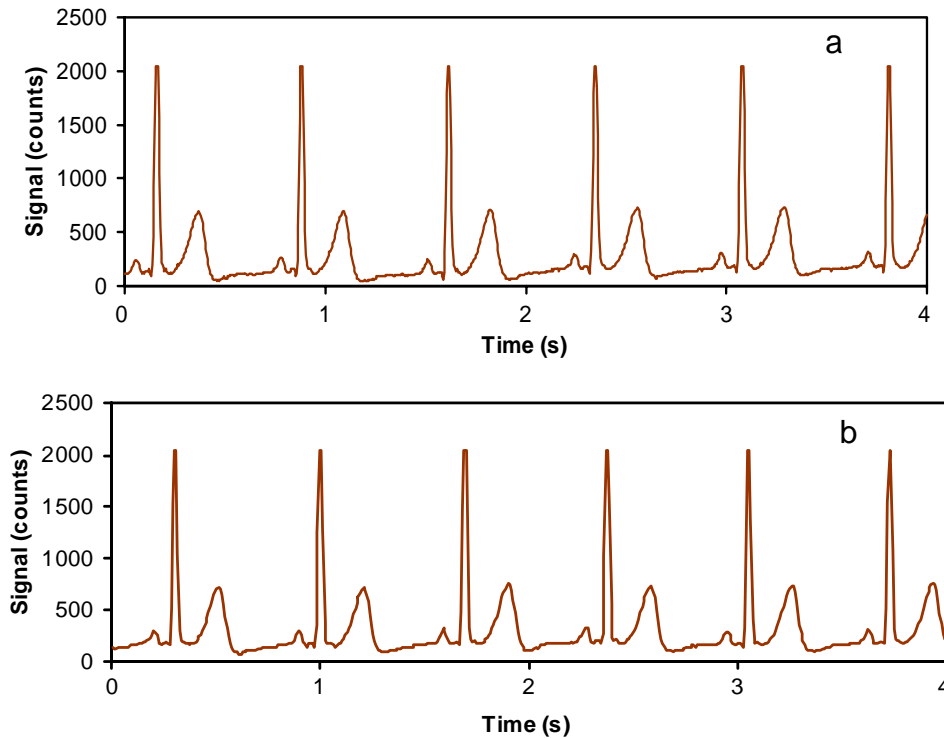


Fig. 8. Electrocardiograms at 256 Hz (a) and 128 Hz (b) sampling rate.

The related research is ongoing world wide. An example of such low-power system is a simple wireless sensor consuming 10 μW [13]. Such sensor can be powered by a very small TEG, because only 1–2 cm^2 of the human body area (depending on the TEG thickness) is needed to get the required power. However, to get a voltage of at least 1–2 V in such a small TEG, film-based miniaturized thermopiles must be developed (see, e.g., [8] and references in it). Otherwise, the low conversion efficiency of power conditioning circuits would cause increasing of the required minimal size of a TEG to a watch-size, which is not an attractive solution for the market.

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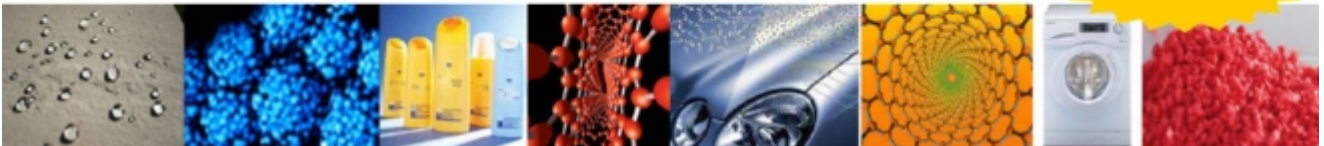
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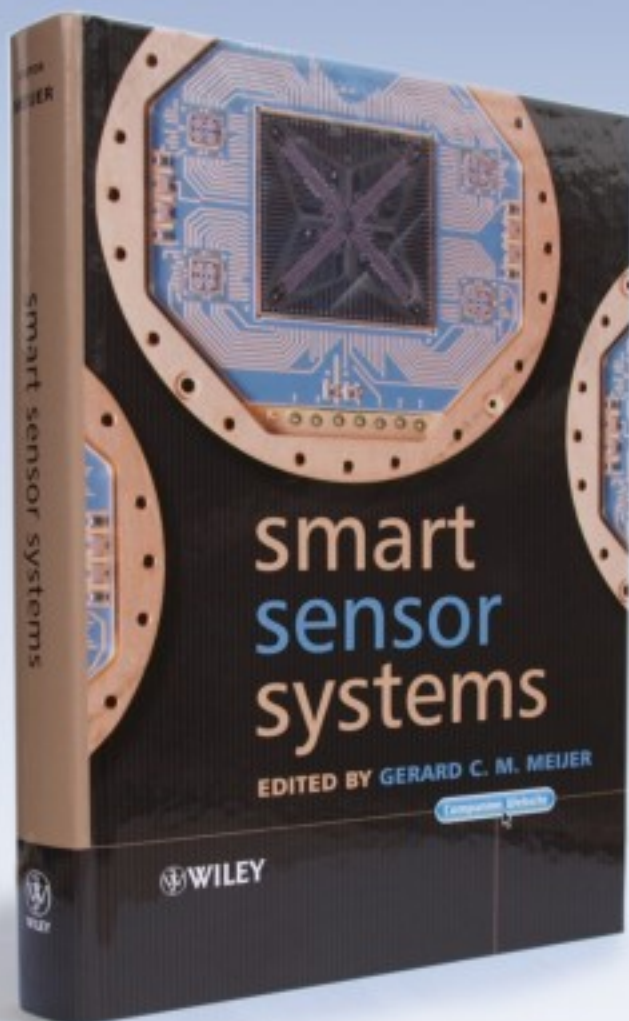
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