HUMAN POWER SOURCE

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Abstract and Executive Summary to the Final Report to the ESTEC Contract No. **: 4000102106/10/NL/AF**

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Abstract

Energy harvesting (also known as power harvesting or energy scavenging) is the process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), captured, and stored. Frequently, this term is applied when speaking about small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks. One of the main advantages is that it makes small devices truly autonomous, since the replacement of batteries will become obsolete. Energy harvesting has many applications, one of which is for use with astronauts. By replacing battery operated systems, the weight and size of an astronauts monitoring system can be greatly reduced. The goal of the Human Power Source project (also referred to as "HEFAISTOS") was to review and investigate the possibilities to use energy harvesting for exactly these applications on astronauts. On the basis of this researchthe developed system harvests power by converting human heat into electricity, and is able to drive a wireless autonomous ECG sensor

1. Background of the study

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More and more effort is nowadays devoted to miniaturising sensors and systems, but this effort is counterbalanced by the fact that batteries are remaining heavy and bulky relative to the sensors. Examples can be found in newly developed human physiology sensors, which now only occupy millimetres in size. The power need of some of these sensors is very low, but the required power sources are still bulky batteries, thus considerably increasing the overall size and weight of the whole system. This is partly due to the fact that such systems need a given autonomy in terms of energy (depending on the foreseen system operation). There is therefore a strong need for designing systems fully compact with regard to sensing and powering elements. This is particularly the case in the field of biomedical engineering as it could be applied to stationary and ambulatory monitoring or feedback systems. The development of alternative and re-usable power sources would therefore benefit a large portfolio of autonomous applications, including space-related applications. For instance, an alternative power system integrated into an astronaut suit could be able to power monitoring, communications or countermeasure systems in a continuous way, and help to reduce payload mass at a large scale. A solution to this could be the direct powering through the human being in terms of energy harvesting from movement, body heat or other means: In general an average person (with around 15% body fat) stores around 390MJ energy [1]). If it would be possible to harvest at least a small fraction of this, the need for batteries (for low power applications) could be reduced or even completely substituted

This general study looked into the possibility to use the human being as power source and assess the relevance of its use for space applications. The study included:

- an extended literature review and analysis of available technologies and techniques related to harvesting energy from living organisms;
- Development of method(s) capable of powering low-consumption devices;
- A verification of these methods;
- A defintion of preliminary requirements for use in space.

This document is a summary of all the findings. It starts with a very general introduction to energy harvesters, followed by a discussion how energy can be harvested in space environment. Next, it looks into possible applications for astronauts, and how these will match with the energy harvesting options. This leads to a system design concept, and the necessary elements will be discussed, before coming to a conclusion.

2. Introduction into harvesting

Energy harvesting (also known as power harvesting or energy scavenging) is the process by which energy is generated from external sources. Energy harvesting is often used when wireless sensor networks are meant, or vice-versa. However, these are clearly two different things, and readers can be easily confused. Therefore, clear definitions are needed upfront to differentiate the many components of which a wireless sensor network is composed. In order of increasing complexity, the following elements can be identified(see *Figure 1*)

- *Harvesting Devices*: these are the means by which energy is transformed into a voltage and current.
- *Power management*: it refers to the circuit used to condition the voltage delivered by harvesting devices for use or storage by using, e.g. AC/DC or DC/DC conversion;
- *Energy storage system*: it refers to the energy storage device used as an energy buffer, such as a supercapacitor or a rechargeable battery;
- *Sensor system:* The system that senses an external signal
- *Micropower Module*: The Harvesting device, connected to a power management system (AC/DC or DC/DC conversion) and an energy buffer (Supercap or a rechargeable battery)
- *Integrated Sensor System*: Powered by the micropower module, consisting of a sensor, a Front End, a DSP, and a microprocessor.

The system can be wireless (*Wireless Sensor Node*). The Integrated Sensor System is equipped with a radio to transmit data. Or even it can be part of a network (*Wireless Sensor Network)* with multiple Sensor Nodes forming a wireless network.

There are many sources for energy harvesting. Since this study is specifically about astronatauts, the energy has to be harvested from the human body. There are three main principles which can be applied:

1. Thermal harvesting: The heat flow from human body can be converted into electricity, using the Seebeck effect. The temperature gradients in case of human body are typically very low, and efficiencies are in the order of 0.1%. Also, the power extracted from the body needs to be limited, to prevent cooling of the skin, which leads to uncomfortable feelings.

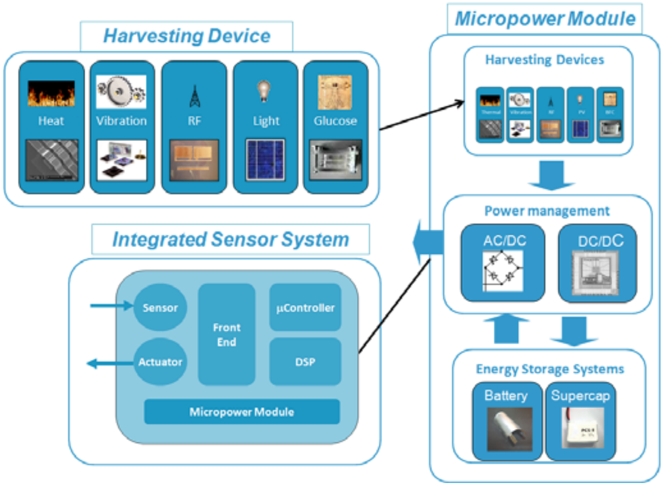

Figure 1:The definition and elements of a wireless sensor node

2. Vibration harvesting: Vibrations can be converted into electricity by using the piezoelectric or electrostatic effect. Motion-driven generators generally fall into two distinct categories: those equipped with an electromechanical transducer rigidly connected to a source of vibration/motion (resonant type) and those using inertial forces acting on a movable proof mass for exciting the transducer (strain type). For human body applications, the latter will produce the most power
3. Biochemistry: Bio fuel cells are electrochemical devices that can directly transform chemical energy to electricity. In a human body, glucose can be used as a fuel.

Of these technologies, the vibration and thermal harvesters are the most mature. Already the first commercial products are being sold, whereas the bio fuel cells are mainly in an academic phase. One has to be aware that it really depends on the application and the environment, how much energy can be generated in the end. Since these factors were unknown at the beginning of the project, two more harvesting technologies have been added to reduce the risk of ending with no feasible solution. Strictly speaking, these solutions cannot be called human body energy harvesting. In addition to the above three, two more solutions are proposed as following:

4. Light harvesting: light from illumination sources can be used to generate power using photovoltaic cells. In space, this can be direct sunlight falling into the spacecraft, or the lighting system installed in the spacecrafts.
5. RF energy transfer: Using RF technology, energy can be *transferred* from a base station to a receiver. Antennas on the human body can pick up the energy radiated by specially designed radiation sources. The energy transferred depends on the distance, the wavelength and the size of the antenna.

For a more in depth discussion, the reader is referred to [2].

3. The Space environment and harvesting

At the beginning of the project, a working meeting has been organized, in order to get input from experts about living conditions of astronauts as well as specific requirements for sensing. Affiliated with world-class research institutes, e.g. CSEM, and universities, e.g. MIT, the external experts brought in their expertise on locomotion of astronauts, vital body parameter monitoring and space transportation, instrumentation and measurement techniques. Based on their valuable input, the possibilities fo energy harvesting in space could be worked out.

Bio Fuel Cell: The bio-fuel cell is the most straightforward: it has the advantage that it will function in exactly the same way in space as on the ground. However, it is ‘early research’ which is presently performed mostly at universities. It is still a long way to go before these devices will be miniaturized. The acceptance by the astronauts of the implantable sensors and eventually the BFC technology may constitute an important challenge. This is one of the important show-stoppers for implementing implantable body-area network technology for space applications that has been mentioned during the technical working meeting

Thermoelectric harvesting: This technology has clearly been an interesting option already from the beginning. Two user scenarios can be identified: The first user scenario is that astronauts dressed in short-sleeve shirts wear miniaturized thermoelectric generators (TEGs) directly on human skin inside a spacecraft (scenario A). The second user scenario is that astronauts wear special space suits integrated with miniaturized TEGs outside a space station (scenario B). Both user scenarios take advantage of the temperature difference existing between human body and the ambient for thermoelectric energy harvesting. In scenario A the ambient temperature inside a space station is supposed to be under strict control and similar to the terrestrial environment. Scenario B has the advantage that a larger temperature difference is available. However, the integration into a space suit is not that straightforward, and might involve serious redesign of the suit. Furthermore, given the strict constraints on the suit, it might prove impossible to have a TEG inside the suit. For the remainder of the study, only a TEG directly on the body is considered

Vibration: Vibration harvesting would be possible inside the astronaut’s boots, or by making use of piezoelectric patches applied on the knees or elbows, generating power each time the astronaut moves. It was shown in the literature that a human with a weight of 68 kg, produces 67 W of energy at the heel of the shoe [2] when walking (on the surface of earth). Harvesting this energy fully would interfere with his gait but a small amount of energy, sufficient for powering a variety of applications, can be extracted without reducing the comfort of the user Figure 2 . For astronauts this will not work, since most of the time they are floating in zero gravity.

It is possible to attach patches of flexible piezoelectric or electrostrictive material on pieces of clothes worn by the astronauts, as illustrated by Figure 2. Maximum energy is generated when the patches are located on the body joints, namely on the knee or the elbow. Motions of the knee joint are not often solicited by astronauts, so that the elbow will be a better location. An estimation of the power that can be achieved with a PVDF patch attached tightly to the elbow is given below. It is assumed that a patch of PVDF of dimensions equal to 150mm×50mm×50µm undergoes a sinusoidal tensile deformation with an amplitude of 5 mm (close from the yield limit of the patch) and a frequency of 1 Hz. The axis of the deformation is aligned with the axis 1 of the patch (largest piezoelectric constant). It is more reasonable to say that energy in the range of tens of mJ per flexure of the joint could be achieved. Note however that, in order to reach the 5 mm tensile deformation assumed in the computations, the PVDF patch should be tightly coupled to the elbow motion (very tight clothes) and the additional physical effort required to deform the patch may be uncomfortable for the user.

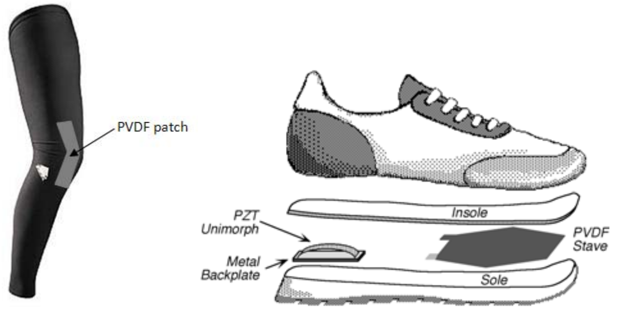

Figure 2: Energy harvesting on knee or in a shoe are enabled by PVDF material

RF: The big advantage of employing RF energy harvesting for on body applications is that these applications may be placed anywhere on the body. The only concern is whether enough power is available in RF signals in the surrounding of the body. The used operational frequency is also associated with this concern. A relatively low frequency has the advantage of a low path loss but the disadvantage of needing a relatively large receive antenna (The receiving antenna size is directly related to the wavelength which is inversely proportional to the frequency). The opposite is true for high frequencies: the path loss is higher but the antenna size is smaller compared to lower frequencies.

Ethernet 802.3 (2.4 – 2.4835GHz, maximum allowed EIRP: 100mW) is used aboard ISS [3]. The receiving antennas for the frequency being used may be as small as a few square centimeters, the rectifying antenna (rectenna) as a whole can be fitted into a volume of a few square centimeters having a thickness of 2mm or less. In the following paragraph, the power available for RF harvesting is studied as a function of frequency within a space station module. For an EIRP of 100mW, a wavelength of 0.122m, a reference distance r_0=1m and a receiving antenna gain of 3 (small printed antenna of a few square centimeters), we have calculated the received power inside the spacecraft as a function of distance. For comparison the free space received power (n=2) is also calculated. The results are shown in Figure 3.

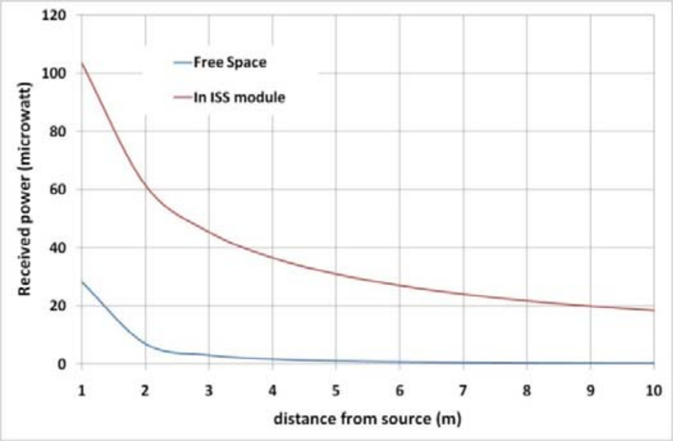

Figure 3: Received power as a function of distance for EIRP=100mW, G_r=3, λ=0.122m and r_0=1m.

The figure shows that at a distance of 10m, still 20µW is available. When multiple receiving antennas are being used (which seems to be feasible due to the small size of the assumed antenna) or when more than one Ethernet router is present, this power level will increase.

PV: In order to evaluate the possible power to be delivered by photovoltaic cells, the lux levels need to be known in the spacecraft. An excellent overview of the typical luminance levels can be found in [4]. The authors have measured the luminance in one 10 and one 16 days space shuttle flight.
Large differences can be found in the different locations inside the spacecraft. On the flight deck, a room with access to sunlight, the light levels are high, but also change a lot periodically to very low levels. This coincides with the rotation period of the spacecraft around the earth: the levels vary between 10^5 and 10^{-1} Lux. In the middeck and Spacelab, only artificial light is present, and illuminance levels are in the order of 10 to 100 Lux.

The authors have also calculated the average levels of luminance, taking into account the typical activities of the astronaut. From these numbers one can estimate the typical lux levels to be in the order of 200-5000 for locations with access to sun light, and 10 to 100 for other locations.
One has to be aware that these values will not be the same for all spacecrafts, but they will give a rough indication of the levels to be expected.
The power output of several photovoltaic cells has been determined, suited for indoor use. This leads to a list of power output per cm^2, for different light sources (e.g. incandescent light, LED, ..).

From the results of the light levels coupled to the power output of the different lighting systems, the power levels that will be reached inside the spacecraft can be derived (*Table 1*). A large spread has been found between the minimum value (1µW/cm^2) and the maximum value of 1mW/cm^2. In worst case scenario, an area of 100cm^2 is needed to get 100µW. This would mean that an area of around 10×10cm is needed. The above values are calculated, assuming an amorphous Si PV cell. These are rigid. If a conformal PV cell is preferred (e.g. organic), then the area needs to be larger, to compensate for the loss of PV cell efficiency. Typically, a-Si reaches 12%, whereas OPV can deliver 6% efficiency, increasing the area by a factor of 2.

Since there is no real up and down in a spacecraft, one can expect the lighting to be omni-directional. This means that most likely all positions on the body will give the same power output. Especially at the back of the astronaut, an area larger than 10×10cm^2 is available.

Table 1: Estimated Power delivered by PV cells inside spacecrafts

Location	**Min and Max Irradiance (Lux)**	**Typical Power levels (µW/cm2)**	
		Min	*Max*
Flight deck	200-5000 Lux	30	1000
Lab spaces	10-100 Lux	1	10

4. Possible Applications for Astronauts

At the same working meeting with the external experts where the energy harvesting options were discussed, also the issue of desired sensing options has been discussed. The options ranged from very simple solutions (e.g. heart rate watches) to more complicated devices. The really simple solutions were discarded, since they do not generate a lot of interesting data, and also they only need a very minute amount opf power, with a small battery giving them enough autonomy (as can be understood easily, data “rate” and energy consumption are closely related). Of all the options discussed, the following three turned out to be the most interesting.

A. SPO$_2$

Astronauts need to do physical exercises regularly in order to minimize the impact of microgravity. Regular exercise maintains bone mass, muscle strength and cardiovascular capacity. Several types of exercise have been planned for the International Space Station. Running on treadmills offers a superior workout for maintaining bone strength. The astronauts need to do such physical exercises for one to two hours every day in the International Space Station, where they can stay for months. When doing physical exercises extra supply of oxygen is usually needed for the human muscles. The blood oxygen can be monitored by using the presented finger pulse oximeter, as shown in *Figure 4*(a). The pulse oximeter is a particularly convenient non-invasive measurement instrument. It is based on the different absorption behaviors of red light (wavelength of 660 nm) and infrared radiation (wavelength of 905, 910 or 940 nm) between oxygenated and deoxygenated body parts. Because the oxygen concentration is associated with the heart beat, an oximeter can also measure the rate of heart beat. When a decreasing level of blood oxygen is identified, the ambient should then be ventilated with more fresh air. Thus, the aerobic exercises can be maintained to have an optimal effect.

B. Sleep monitoring/Electroencephalography (EEG)

Sleeping in outer space remains much more difficult than on the Earth. In the microgravity environment, the astronauts need to attach their bodies to a wall, a seat or a bed, as shown in *Figure 4(b).* Otherwise, they are floating in the crew cabin. The normal sleeping patterns can be disrupted by the orbiting around the Earth. Note that each circuit around the Earth takes only about 90 minutes. That means that the interval between sunrise and sunset is about 45 minutes, significantly shorter than that on the Earth. In addition, the quality of sleeping tends to be compromised by the noises from the spacecraft itself and the tension of carrying out demanding tasks. On the night before a spacewalk, only 50% of astronauts are able to sleep for less than five hours due to anxiety and their uncomfortable surroundings[5]. Improving the sleep quality starts with the sleep monitoring, which could be approached by using an EEG headset. EEG is the recording of electrical activities resulting from ionic current flows within the neurons of human brain. The EEG is used along with other measurement methods to define various sleep stages. One needs to note that the traditional method to carry out EEG is based on an array of wired electrodes. The unwieldy wired connections for power supply and data transmission can largely compromise the sleep quality as a hindrance to the free movement of the body during sleep. This deficiency can be properly addressed by exploiting the wireless sensors.

C. Electrocardiography (ECG)

Figure 4: Three selected applications: a) SpO2 b) Sleep/EEG Monitoring and c) ECG monitoring

Space travel presents a drastic change in working conditions to the heart. Often, astronauts who have just returned from space have difficulty maintaining normal blood pressure and blood flow when standing. Without gravity to contend with in outer space, the heart has to do far less pumping work. Heartbeat thus slows down. Since the body no longer needs to maintain the powerful heart muscles needed on the Earth, heart tissue begins to shrink. In another area of cardiovascular research, it was found that exposure to space impairs an astronaut's pressure-regulating reflexes, called “baroreflexes”. As shown in *Figure 4(c)* one could wear a wireless ECG necklace for heart activities monitoring, when carrying out daily operations. The wireless ECG sensor in the shape of a necklace is a proven robust technology with extreme low power consumption. It can continuously work for 24 hours a day for a full week with a fully charged battery. The heart activities can be visualized on a hand-held device on real-time basis. Similar to the aforementioned two scenarios, the ECG necklace can also be powered by the human body.

5. Choosing the best energy harvesting option

After the discussion of the most suitable applications, the attention is now shifted back to the energy harvesting technology. One has to compare the different harvesting options based on a few key criteria like power, distance to sensor, comfort, size, etc. Before one can determine this, one needs to know the specific features of a harvesting in combination with one of the specific applications mentioned before. In Table 2, the possibilities of various harvesting technologies are compared when used in the three application scenarios.

Clearly, the TEG can be deployed on the wrist, on the forehead and in a shirt respectively for pulse oximeter, sleep monitoring and heart activity monitoring. In comparison, PV and vibration harvesting both have their own shortcomings, such as large area or long wired connections. Although RF energy transfer is possible in all the three cases, it is not a human power source per se.

The results from Table 2 are input for Table 3, where the different energy harvesting technologies are examined against several key criteria, namely power, distance to sensor, unobtrusiveness, comfort, dimensions and thickness.

Finally, some extra information has been collected, which clearly points to the differences between the technologies. These are listed in *Table 4*. First of all, the major distinction between the PV cells and RF transfer devices on one side, and the thermoelectric and vibration harvesters on the other side, is that the former category needs external input, while the latter category is directly powered by human body.

Table 2: Summary of applications and energy harvesting

	Pulse Oximeters	**Sleep monitoring**	**Heart Activity**
Thermal	Possible location of TEG on the wrist	TEG can be placed on head	TEG can be implemented in a shirt
PV	Need large area of PV, possibly at the back. Need long wires to sensors	PV needs to be integrated into sleeping bag	Need large area of PV, possibly at the back. Need wires to sensors
Vibration	Harvesting to be at the knee or elbow. Need long wires and large battery	Energy harvesting not possible during use. Only by using stored energy	Harvesting to be at the knee or elbow. Need long wires and large battery
RF	Possible location on the wrist	Possible location on the headset, or on the body with long wires attached	Can be located very close to the heart with a belt

Table 3: A comparison of the 4 result of the EH options. White, grey or dark color means that criteria are met, are within reach or differ very much from specs, respectively.

Typical values	Thermal	PV	RF	Vibration
Power	+	-	-	+
Distance to sensor *(cm, max)*	10	150	0	100
Unobtrusiveness	+	+	+	0
Comfort	0	+	+	0
Dimensions (cm^2)	10	100	10	10
Thickness (cm)	1-2	0.5	2	0.5-1

Next, when comparing the thermoelectric with the vibration solution, it is clear that the energy output is more clearly defined and more uninterrupted in the case of thermal harvesting. Furthermore, maturity levels are also listed, reflecting the stage of development. PV cells are the oldest technology and most mature with widely available products. Vibration harvesting of the strain type is still under development. The RF transfer and the thermoelectric harvester for human body applications have not been made into products yet, but only need further integration of existing components.

Based upon the different application scenarios, the thermal harvester turns out to be the best choice for further development into real prototypes. Furthermore, the ECG case enables to design a device which is invisible and gives the most comfort to the user, in this case the astronaut.

6. System concept

The final design for the ECG monitoring device, consists of 4 parts: a) the thermal harvester, b) the power management, c) the energy storage solution and c) the sensor system. In the sections below, all these elements are discussed and some of their main characteristics are presented.

Table 4: Comparison of maturity, deployment and energy source for the different energy harvesters

	Thermo	PV	RF	Vibro
Maturity	0	+	0	-
Deployment	Tight fitting to body and clothing essential	Large area should be flexible	Extra transmitters and receivers needed	Tight contact to clothing essential
Energy source	Human body	External conditions	External conditions	Human body
Remarks	Energy source 24hrs available, independent of astronauts activity	Large variation of power. Dependent on time and also differs between different space crafts	Large variation of power depending on position of transmitter and also differs between different space crafts	Energy highly dependent of astronauts activity scenario

A. The thermal energy harvester

Various ways of integrating TEG modules into garments have been investigated. The TEG can be mounted through a hole in the shirt so that it makes direct contact with human skin and the ambient. Alternatively, the TEG can be completely covered by the textile and extra heat-spreading layer and thermally insulating spacers can be inserted. The slim-fit shirt ensured mechanical contact of cotton with the cold plate of the module. The cotton performed the role of a radiator, while the cold plate made of aluminum was used as a heat spreading plate interconnecting thermally a thermopile and a cotton radiator. The Al plate with dimensions of 3 cm×4 cm effectively spreads the heat over a textile.

It is commonly believed that thermally insulating materials like textile cannot be effective if used as radiator material. However, the thermal resistance of textiles is not high as compared with the thermal resistance of the module required for maximum power generation in a wearable device [6]-[7]. The former is of the order of a few tens cm^{2}K/W. An optimized wearable thermopile must show a thermal resistance by a factor of about 10 higher. Therefore, one should expect only minimal loss of power if the TEG is coated by a thin layer of textile.

Measurement results of experiments on the leg of a human body are shown in Figure 5. The power produced by a TEG covered by textile improved by about 8% [8]. The heat that spreads in textile around the cold plate causes essential increase of the effective area of the radiator. Therefore, the textile-based radiator had in all above experiments larger effective area than the area of heat spreading plate. This is the simplest way of integration of a TEG in garments.

The same effect has been observed for the TEG in a shirt. The heat transfer in the textile itself near a TEG can also be enhanced locally by direct weaving heat transfer means such as metal wires or carbon fibers, or textile could be filled near a TEG with thermally conducting glue for locally enhancing its heat-spreading ability. As a result, textile can function as effective fabric radiator.

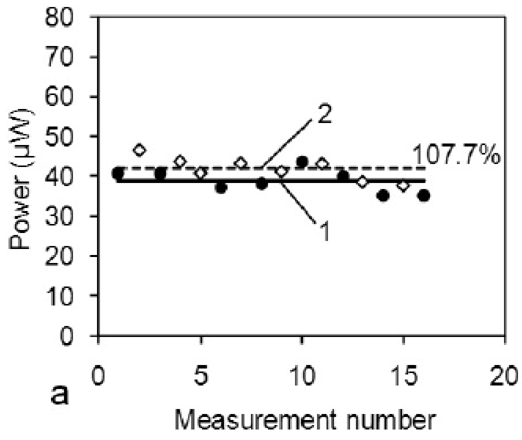

Figure 5 The power of the TEG on a human leg covered by textile (open diamonds 2) increases as compared to the same TEG in the same location if it is not covered by textile (closed circles, 1). [8]

Based on the obtained results, the TEG with sixteen one-stage thermopiles from Thermix (with about two thousand BiTe thermocouples in total) has been designed, fabricated and integrated into an office-style shirt, Figure 6a. Thermopiles employ thermoelectric legs with lateral dimensions of 310 µm and an aspect ratio of 8. For shock protection and heat transfer enhancement, hot plates of 3 cm in diameter and cold plates of 3 cm × 3.5 cm size are glued to thermopiles. Thermopiles with two plates have a thickness of 5 mm. They are mounted on a piece of cotton, Figure 6 (b). Two large pieces of carbon fabric are sewed and glued on the inner side of the shirt, on the left and right side of the chest. Carbon fabric occupies an area of 0.075 m^2. Then, the piece of cotton with mounted thermopiles is sewed to the shirt from inside, and cold plates of thermopiles are glued to carbon fabric. Therefore, the device and wiring are hidden between two cotton layers and invisible from either side. Unlike devices reported in the literature earlier, the new TEG does not require any modifications to existing garments: it is just glued and sewed to the shirt purchased in a shop. The device is truly unobtrusive because of cotton layer on the skin and a flexible cotton radiator. For good heat transfer from the skin to the TEG, the latter must be attached with no air gap. There are no elastic bands integrated in a shirt. This causes periodic detachment of some of thermopiles from the skin and decreases the power produced on average. However, this approach enabled further improvement of comfort of the subject.

The measurement results show that the hidden TEG with 16 thermopiles and no elastic bands produces approximately the same power (see experimental points in Figure 6 (c)) as 14 thermoelectric units with elastic bands and external 3 cm × 4 cm plates in the previous designs. The points of a standing or sitting person (open triangles) and on a walking person (closed circles) are plotted. For comparison, the shown lines correspond to the measured power of the TEG of an electrocardiography shirt with external Al plates in the same conditions. The measurements show that an average power of 1 mW (at 1.2 V on the matched electrical load) observed in the office at 22°C doubles if the person walks in a corridor. The power also doubles at ambient temperature of 17°C, i.e., it increases to 2 mW on a standing or sitting person, and to 4 mW on a walking person, Figure 6(c).

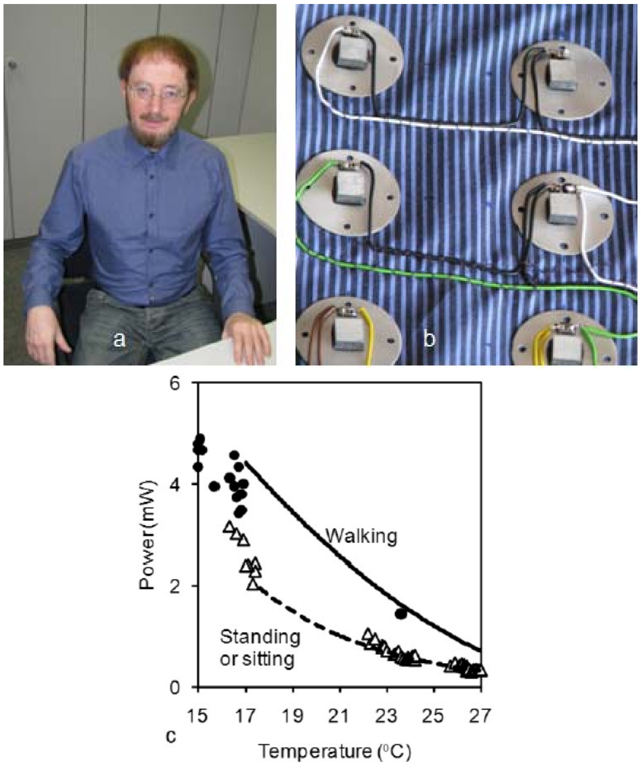

Figure 6: (a) A shirt with hidden thermoelectric generator, (b) thermoelectric modules integrated on the inner cotton layer (6 modules) and (c) the generated power measured indoors and outdoors on a standing or sitting person (open triangles) and on a walking person (closed circles).[8]

B. *The power management unit*

The complete PMC consists of the different blocks shown in *Figure 7*. The main block is the charge pump with a variable number of stages that performs the DC/DC-conversion. Using MIM-capacitors with very low parasitics (α= 0.03), the charge pump has an efficiency up to 80%. The feedback circuit is powered by the output of a linear voltage regulator. When the output voltage is zero, the controller cannot function and the output is charged through the diode in the charge pump. When the output voltage exceeds 0.9V the controller starts working. The current sensor copies the current that flows to the output, a capacitor is charged by this current and the resulting voltage across the capacitor is provided to the control circuit. This voltage is also a measurement of the power flowing to the energy buffer. The digital control algorithm sets the number of stages M and the switching frequency f by maximizing the current that flows into the buffer. This can be done because the buffer voltage stays constant within a short period, and this makes the output current proportional to the output power. The algorithm and the PMC were presented in [12]. The

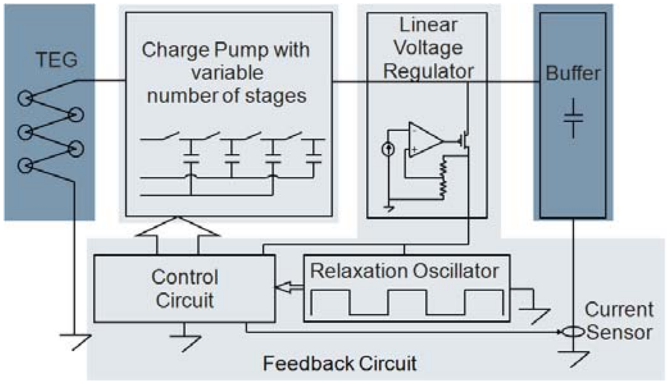

Figure 7 Block diagram of the system ***Error! Reference source not found.*.**

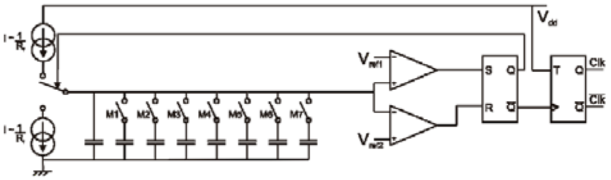

Figure 8: Relaxation oscillator with programmable frequency, parameter R_f fixes the base frequency ***Error! Reference source not found.***

clock circuit drives the control circuit and the charge pump. It is a relaxation oscillator operating at a programmable frequency. The reference frequency is set by resistor R_f that determines the current charging the capacitor of the oscillator. The size of the capacitor is adapted to optimize the frequency when changing the number of stages as shown on *Figure 8*.

R_f is selected according to the expected generated power. A PMC containing a charge pump with capacitors of 2.45nF and a maximum of 8 stages has been realized. The total area is 59mm^2. The measured overall system efficiency, *M* and *f* for a TEG with an impedance of 11kΩ is shown in Figure 8. The circuit starts up at 0.6V open circuit voltage of the TEG when the buffer voltage is 2V. R_f is 22MΩ. The current flowing through the regulator to the feedback circuit is below 1µA. The measured peak efficiency is 70%. With these parameters, the maximum number of stages used is 3 due to the very small difference in output power at the low input voltages. For a higher input power, more stages are used at start-up. This leads also to a lower start-up voltage. When the input power increases, at the higher V_{open}, the output current increases and the voltage drop across the switches is no longer negligible. This leads to a lower measured efficiency than what was calculated and where V_d was neglected.

C. The Energy Storage Solution

The energy storage system has to provide two functions. A) be a buffer to cope with periods of reduced power input and b) Be a buffer to cope with periodically bursts of large currents. A Li-ion battery is the best solution for the aforementioned issues for the reason that it has the largest energy density and can cope with large current variations. The specific battery energy density needed can be calculated taking some worst case scenarios into account:

From the literature, one finds that a typical energy consumption is to be expected in the order of 0.1mW continuously. Only in case of an 8 channel EEG, 1mW is to be expected. Therefore one should take two designs into considerations: For the EEG application and the other one for all other applications.

There might be periods of time, when less or no power is produced. In worst case, one has to take into account that no power is produced for several hours (e.g. periods when the astronaut is sleeping (8h), or when the TEG is blocked.

With the remarks accounted for, one can calculate the battery needs

1) EEG system: During 12 hours, 2 mW needs to be produced by the TEG. During the other 12 hours, the 1 mW is supplied by the battery. For Li-ion, the operating voltage will be in the order of 3.6V. The current need is thus 1mW/3.6V~300µA. This current has to be supplied during 12 hours, so the total battery capacity has to be 3.6mAh.
2) Other systems. The energy need is 0.1mW during 12 hours, so the battery capacity needs to be 360 µAh.

When looking to available commercial systems, one finds that in case 1) (the EEG system), the needed capacity can be provided by a coin cell (Panasonic VL2020, *Figure 9* (a)) or small aluminum packages (GMB201218, *Figure 9*(b)). The coin cell has a voltage of 3V, the GMB the standard Li-ion voltage of 3.6V. For the other applications, a thin film battery like the IPS MEC120 (*Figure 9*(c), 3.6V) with a capacity of 400 µAh could be a solution.

D. The sensor: ECG patch

The ECG patch is chosen as sensor device and is aimed at long-term heart activity monitoring on astronauts. The use of the recently standardized Bluetooth Low Energy (BLE or version 4.0[13]) technology, together with a customized ultra-low-power ECG System on Chip (ECG SoC), including Digital Signal Processing (DSP) capabilities, enables the design of ultra low power systems able to continuously monitor astronauts, performing onboard signal processing, such as filtering, data compression, beat detection and motion artifact removal along with all the advantages provided by a standard radio technology such as Bluetooth. Early tests show how combining the ECG SoC and BLE leads to a total current consumption of only 500µA at 3.7V, while computing beat detection and transmitting heart rate remotely via BLE.

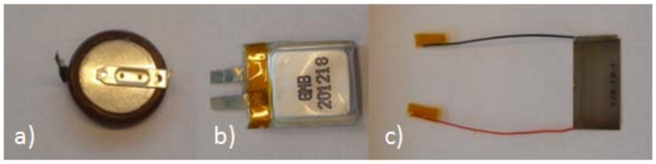

Figure 9: Li-ion batteries from (a) Panasonic, (b) GMB and (c) IPS.

1) *The hardware*

The ECG patch can be functionally divided into two subsystems. The first is the mixed signal ECG SoC [14], which in turn consists of three main parts: an Analog Front-End (AFE), a 12-bit Analog to Digital Converter (ADC) and a custom Digital Signal Processing (DSP) back-end. The AFE supports concurrent 3-channel ECG monitoring, with impedance measurements and band-power extraction. The 12-bit ADC with adaptive sampling scheme, capable of compressing the ECG data by a factor of 5, reduces the power consumption due to data processing and transmission. The DSP back-end, using SIMD processor architecture, hardwired accelerate unit, effective duty cycling, instruction cache, and clock gating scheme, provides low power operation while performing multi-channel ECG processing; additional signal filtering, ECG feature extraction, analysis and motion artifact removal [14]. The second subsystem is the CC2540 BLE SoC from Texas Instruments (TI), which takes care of retrieving the data from the sensors present in the system (i.e. ECG SoC and accelerometer) and sends it to a remove BLE enabled device. Additional components are a 3-axis accelerometer for activity monitoring and a MicroSD card for data logging: they are interfaced to the BLE SoC through a second SPI interface. The system is powered by the aforementioned energy harvester in conjunction with the power management circuit and energy storage system. The system architecture is illustrated in *Figure 10*. Note, that this is the standalone version as implemented in our institute, without the energy harvesting. For the final system to be implemented on astronauts, the Li-Po battery is to be replaced by the Micropower module.

2) *Firmware and data processing*

The ECG SoC implements 3 different real-time monitoring applications. In the data collection mode, the signals are sampled and sent over the SPI interface. Only the AFE is running. The second mode is beat detection. The QRS complex is detected using an algorithm based on derivative or band-power extraction. The last mode performs an accurate R peak search using a continuous wavelet transform algorithm optimized for robustness to motion artifact [15]. The duty cycle of pre-processing unit and processor during the execution of the R-peak detection is 2% and 3% respectively, leaving plenty of space for the implementation of additional algorithms. Currently, two different operation modes are implemented in the ECG patch:

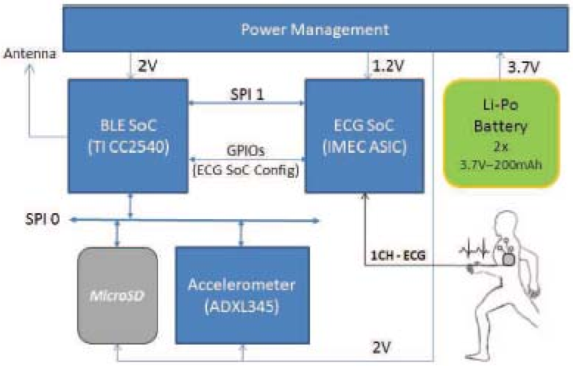

Figure 10: Hardware architecture of the ECG patch. [15]

Figure 11: Mechanical casing and electrode patch.

- Mode 1: beat detection on the ECG SoC and transmission of the heart rate through the BLE SoC;
- Mode 2: streaming of heart rate and acceleration with 40Hz sampling frequency for activity monitoring.

3) *Housing and electrodes patch*

The mechanical casing of the patch has been developed by DELTA [16]. It consists of a disposable patch, hosting the ECG electrodes, and a “smart” cap (2.5 cm in diameter) which contains electronics and 2 batteries (*Figure 11*).

4) *Characterization and tests*

Experimental results show that the ECG SoC consumes 61.1µW at 1.2V while performing beat detection (2% duty cycle). The power consumption of the BLE chip is highly dependent on the data rate of the application, since the BLE protocol is able to reduce to the minimum of the connection management overhead. The average current consumption for Mode 1 is 500µA at 3.7V, as shown in *Figure 12*. One finds that streaming of heart rate and acceleration increases power consumption up to 1mA at 3.7V (mode 2).

7. Towards a prototype

In the previous sections, all the elements of a system have been presented which have been tested in a) lab conditions and b) on earth. The step towards an application for space is not trivial. The main reasons are the requirement imposed by space applications. Specs for reliability, out gassing and acceleration (to name only a few) are much harsher than for earth applications. Therefore, when the step is taken from idea to prototype, these requirements have to be taken into account and ultimately tested. Based on the outcome of these requirements tests, a redesign might be necessary. Already, one can predict some of the issues that are likely to appear. These issues are listed below, discussing them at each of one of the four elements the prototype consists of: Harvester, Power management, ESS and Sensor. . For each of the issues listed, countermeasures are presented.

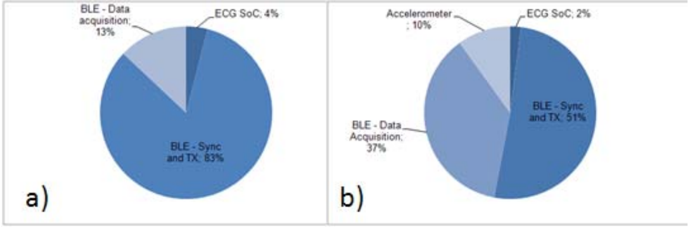

Figure 12: Power consumption breakdown of the ECG patch in a) mode 1 and b) mode 2

The Thermal Energy Harvester

The current design of the harvester, is optimized in power for use on earth. If any of the requirements for use in space is not met (e.g. outgassing, mechanical reliability) a redesign is needed. This will lead to a reduction of total power output (e.g. due to the replacement with materials whcih meet the outgassing spec, but which will be less efficient in power output) This can be compensated by increasing the total area on the body covered with TEG. Another issue will be the manufacturing of the TEG. At this moment, the TEG is composed of thin BiTe rods. The thermopiles employ thermoelectric legs with lateral dimensions of 310 µm and an aspect ratio of 8. This kind of device is relatively expensive and very hard to produce many devices per year (max 10-20/year) If more devices are needed, there might be an issue. Then one has to start using micromachined devices, where one can make many thermal harvesters in one batch using micromachining. There are a few companies already making micromachined BiTe based thermal harvesters e.g. Micropelt [17]. However, these devices cannot simply be applied on a human body, since they are all optimized for applications in machine, at locations where temperature gradients are in the order of 10 to 50K and the thermal resistance is very low. Without redesign, these devices will not produce any power when applied on the human body. A redesign is essential, but time consuming

Power Management IC

The power management IC was designed with 0.35µm CMOS technology. A first design of this IC is ready. Currently, the efficiency is in the order of 70%. This IC is functional, but still redesign is desirable. First of all, new ideas on how to further increase the efficiency need to be implemented. Secondly, some functionalities need an update (e.g. maximum power point tracking), since they do not yet work optimally. Finally, extra functionalities might need to be added. However, no real showstoppers are foreseen here. Since IC's have been used for many years in space, the stringent requirements should easily be met.

Energy Storage System

The ESS part is the most unknown factor in our case. From an energy and power density point of view, all the informationof the various commercial systems are available. However, no information on requirements as fit of materials, radiation hardness, out gassing and protection against interference has been made public. . The results of the requirement testing are therefore essential to gather this data.

The Sensor System

With regard to the sensor, it has already been tested on human bodies and the needed power levels are known. From a point of functionality, no major roadblocks is to be expected.

The main unknown factor here will be the specific space application requirements. None of the sensor parts have ever been tested at the harsh conditions as described in the requirements document. The functionality in space is therefore not guaranteed. Any subsequent project will thus need to address this issues if necessary

8. Conclusion

In the framework of ESA-HPS project, a conceptual design of a human power source for ECG patches on astronauts has been developed. The design is based on IMEC technical expertise in the relevant associated technologies. However, this design might not be translated one-to-one towards the application specified by the space requirements. A major issue will be the following: The design is based on experience with long-term health monitoring on the elderly and the chronically ill. For such applications, the technical requirements are less stringent than those for space applications. Moreover, space application imposes more requirements, such as out gassing and radiation hardness. Therefore, it is possible that the design proposed in the project will not properly meet all the technical requirements for space application. Iteration steps towards optimization and reliability tests are required in a subsequent project that will realize a prototype.

9. Acknowledgement

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