32nd Annual International Conference of the IEEE EMBS
Buenos Aires, Argentina, August 31 - September 4, 2010

Energy Harvesting for Human Wearable and Implantable Bio-Sensors

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Abstract— **There are clear trade-offs between functionality, battery lifetime and battery volume for wearable and implantable wireless-biosensors which energy harvesting devices may be able to overcome. Reliable energy harvesting has now become a reality for machine condition monitoring and is finding applications in chemical process plants, refineries and water treatment works. However, practical miniature devices that can harvest sufficient energy from the human body to power a wireless bio-sensor are still in their infancy. This paper reviews the options for human energy harvesting in order to determine power availability for harvester-powered body sensor networks. The main competing technologies for energy harvesting from the human body are inertial kinetic energy harvesting devices and thermoelectric devices. These devices are advantageous to some other types as they can be hermetically sealed. In this paper the fundamental limit to the power output of these devices is compared as a function of generator volume when attached to a human whilst walking and running. It is shown that the kinetic energy devices have the highest fundamental power limits in both cases. However, when a comparison is made between the devices using device effectivenesses figures from previously demonstrated prototypes presented in the literature, the thermal device is competitive with the kinetic energy harvesting device when the subject is running and achieves the highest power density when the subject is walking.**

I. INTRODUCTION

In order for any wireless bio-sensor device to be truly convenient for the wearer it should not require user intervention. As a consequence, the power supplies for such devices should be maintenance-free and able to supply power as required for an unlimited time period. Batteries are of course the most common supply for portable electrical devices but are exhaustable sources. Since the late 1990s there has been a significant research interest in miniature energy harvesting devices which turn ambient energy in the form or motion, thermal gradients, light or electromagnetic radiation into an electrical form in order to supply power to nodes in wireless sensor networks. There are now several companies selling motion-driven energy harvesters for use in industrial environments [1], [2]. In these applications the energy harvester typically converts high frequency, low amplitude machine vibrations into electrical energy. Such devices are capable of harvesting tens of mW, depending on their size and the vibration characteristics of the source to which they are attached [3].

Harvesting energy from human body motion for powering a bio-sensor is often significantly more difficult than extracting energy in a vibration and temperature rich industrial machine environment. The increased difficulty arises mainly from the fact that there may be significant size constraints on the harvester in the human scenario (typically less than 1 cm^3) and that human motion occurs at much lower frequency. For thermoelectric devices, the fact that thermal gradients between the human body and ambient or gradients within the human body are substantially lower than those seen in an industrial plant also makes thermoelectric harvesting on the body a challenging task.

Starner investigated the possibility of powering a computer from energy harvested parasitically from a human in [4]. In that work, the limits of the energy that could be extracted from a human with relatively large generation devices is discussed, including a generation device embedded in a shoe. The same concept was further developed in [5]. Some types of energy harvesting device suitable for harvesting energy from the human body can be hermetically sealed (such as solar, thermal and inertial kinetic devices) and some, such as fuel cells which use chemicals from the body to generate power, cannot. The sealability of such a harvester may be necessary for a bio-sensor in terms of safety. Therefore, in this paper, a more detailed analysis of the two most promising types of hermetically sealable and miniaturisable energy harvesting devices for use in or on the body, *i.e* inertial kinetic and thermoelectric devices, is presented.

II. INERTIAL KINETIC ENERGY HARVESTERS

Several devices have recently been reported which are designed to harvest kinetic energy from the human body, including a knee brace [6] and a back-pack [7]. Whilst these devices can generate hundreds of mW whilst the wearer walks, their construction, size and mounting location on the body is not suitable for use with miniature and unobtrusive bio-sensors.

A more suitable and readily available commercial energy-harvesting device for powering bio-sensors from human body motion is the energy harvester mechanism from a kinetic watch, such as those manufactured by Seiko [8]. The energy harvester in such a watch occupies around one quarter of the total device volume and comprises an unstable mass pivoted in the centre of the watch (in the form of a pendulum). As the wearer moves, the unstable mass rocks and turns a miniature electromagnetic generator. An average power of around 10 μW can be expected over a typical day when the watch is worn. Whilst this power level is enough to perform bio-sensing and information transmission, possibly with a duty cycle of less than unity, the power generated would of course be significantly lower if the user is immobile, or if the

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bio-sensor is not worn on a limb, as the device must move through relatively large displacements in order to excite the generator's heavily damped unstable mass.

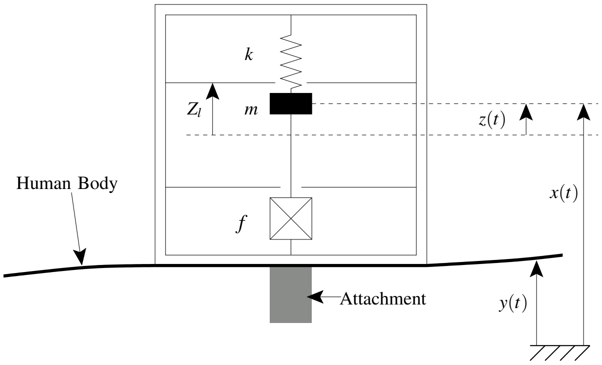

Fig. 1. Inertial generator attached to human body

A schematic of a conventional MEMS-compatible and miniaturisable inertial micro-generator which might be strapped to the human body is shown in Fig. 1. It has previously been shown that the limit of the power generated from a linearly-excited motion-driven generator with linear proof-mass motion mounted on a walking person is between 1 and 4 μW for a device occupying around 0.25 mm^3, rising to between 0.5 and 1.5 mW for a generator occupying 8 cm^3 [9]. Generators occupying several cubic centimetres may be acceptable for body-worn devices but would have limited use as implantable devices.

An upper limit of the power generated from a vibration-driven device in a human worn application can be shown [10] to be

$$P_{max} = 2\frac{Z_l Y_0 \omega^3 m}{\pi} \tag{1}$$

where Z_l is amplitude of the inertial mass motion, Y_0 is the amplitude of the driving motion, m is the value of the proof mass and ω is the angular frequency of the driving motion, as indicated in Fig. 1. If we assume that any inertial-based generator will be cubic in shape, we can rewrite the expression for the power available as a function of the length of one side of the cube:

$$P_{max} = \frac{1}{16} Y_0 \rho L^4 \omega^3 \tag{2}$$

where L is the length of a side of the cube and ρ is the density of the proof mass, which is assumed to be lead with a density of 11340 kg/m^3.

In [9], a typical measured position waveform that a kinetic-energy based generator would be subjected to is presented for the condition that the generator is mounted on the lower leg whilst the person is walking at 4 km/h. The amplitude is estimated as 0.15 m and the excitation frequency as 0.8 Hz. In this paper, it is assumed that when a person is running at 12 km/h, Y_0 would increase to 0.25 m and the excitation frequency would increase to around 2 Hz.

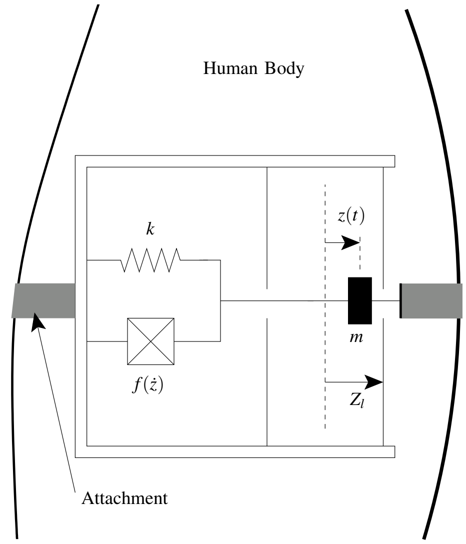

Fig. 2. Direct-force generator attached to human body

The power output of an inertial generator of fixed volume can be increased by constructing the device in an aspect ratio that is long and thin, allowing the proof mass to move through a larger swept volume, maximising Z_l. Such a form factor of device, similar to that of the implantable Verichip RFID product [11], may be advantageous in terms of ease of insertion in the body with a needle, however, the difficulties in realising such a device at a small scale are increased if such an aspect ratio is to be used. Therefore in the analysis presented in this paper, a cubic device is assumed.

III. DIRECT-FORCE KINETIC ENERGY DEVICES

The fundamental way to maximise power output from motion-driven devices is to maximise both the force acting on the transducer and the distance through which the transducer moves. As the distance the proof mass can move is limited by the volume and practically achievable aspect ratios of the device, it is highly desirable to increase the force acting on the transducer. This can normally only effectively be achieved with a non-inertial device in which a force can directly act between the two ends of the transducer, rather than in an inertial device where the transducer force is limited by the limited inertia of a finite size proof mass. Such a generator could take the form of a stretchable piezoelectric band around a contracting muscle or a transducer anchored between two pieces of the body moving relative to each other. Such an arrangement is illustrated in Fig. 2. It should be noted that this type of power supply is likely to only be of use for large, wearable applications because of the difficulty of attachment if the device is to be implanted. In other words, the surgical procedure is likely to be significantly more difficult than a simple battery replacement and thus follow-up battery replacement operations may be preferred.

If the device is to be worn externally, perhaps around a muscle whose diameter significantly changes during normal daily activities, the device is likely to be both large and

relatively obtrusive to the wearer.

IV. SOLAR

Whilst attractive power sources in many ways, partly due to their high reliability due to a lack of moving parts, it is unlikely that solar cells are a good solution to the power supply problem for human bio-sensors. Whilst they are the most mature of the energy harvesting technologies and miniature cells have been demonstrated, availability of light is clearly a significant problem in implantable applications but also also with many wearable applications when worn under clothing. It has previously been shown that thermoelectric devices, also a reliable solid-state technology, are superior to solar cells for BSN applications [12].

V. THERMOELECTRIC

Thermoelectric generators for powering human implantable or wearable sensors are currently receiving increased attention in the research literature. An early example of thermoelectric generators used on the human body is the Seiko Thermic watch. This device, which generated electrical energy by applying the thermal gradient between the skin and the ambient across a thermopile, as illustrated in Fig. 3, was only manufactured for a short time. The Seiko Kinetic watch, however, is still in production. This suggests that the power density for small kinetic energy power generation devices on the human body may be superior to devices that generate from thermal gradients. However, we will now look at the power density of thermal gradient devices in detail in order to allow us to make a quantitative comparison between kinetic and thermal power generation for human-powered applications.

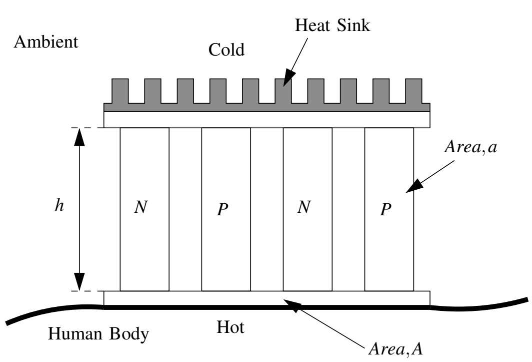

Fig. 3. Thermoelectric generator mounted on human body

It has recently been shown that thermal impedance matching of thermoelectric generators on the human body, as well as electrical impedance matching, is very important in order to maximise the electrical energy generated [12]–[14]. A simple model of the thermal circuit of a thermoelectric generator worn on the human body with the hot junction in contact with the body and the cold side connected to the ambient via a heat sink is shown in Fig. 4. Q_{body} is the rate of heat flow from the human body through the generator, R_{body} is the thermal resistance of the body, R_{sink} is the thermal resistance between the heat sink and the ambient and T_{body}, $T_{ambient}$ and ΔT_{TEG} are the core body temperature, ambient temperature and temperature difference across the generator's hot and cold sides respectively.

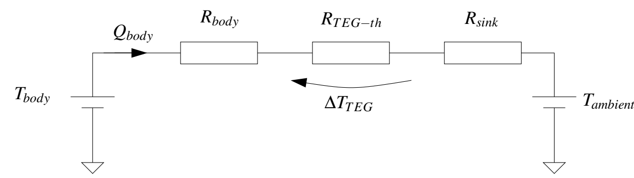

Fig. 4. Thermal equivalent circuit for thermoelectric generator attached to body

From Fig. 4 it at first seems sensible to make the thermal resistance of the generator, R_{TEG-th}, as large as possible so that the majority of the temperature gradient between the body core and the ambient occurs over the generator itself rather than across the thermal resistance of the body tissue or the heatsink-air interface. However, a simplified analysis based on that presented in [14], shows that this is not the case. With reference to Fig. 4, the temperature difference across the hot and cold sides of the thermoelectric material is given by:

$$\Delta T_{TEG} = \frac{R_{TEG-th}}{R_{TEG-th} + (R_{body} + R_{sink})}(T_{body} - T_{ambient}) \quad (3)$$

The maximum electrical power that can be extracted from the generator occurs when the load is electrically impedance matched to the internal resistance of the thermoelectric generator and is thus given by:

$$P_{max} = \frac{(n\alpha\Delta T_{TEG})^2}{4R_{TEG-el}} \quad (4)$$

where R_{TEG-el} is the electrical resistance between the terminals of the generator and α is the generator Seebeck coefficient. The thermal resistance of the generator can be written as $R_{TEG-th} = h/(K_{TEG} \cdot na)$, where K_{TEG} is the thermal conductivity of the thermoelectric material, h is the distance between the generator hot and cold junctions, a is the cross-sectional area of each thermoelectric pillar and n is the number of thermoelectric pillars, as illustrated in Fig. 3. The electrical resistance of the generator is given by $R_{TEG-el} = \rho nh/a$, where ρ is the electrical resistivity of the thermoelectric material. Substituting these equations into Eqn. 4, it can be shown that maximum electrical power is generated when the thermal impedance of the generator is equal to that of the thermal resistance of the other parasitic thermal resistances along the path of heat flow from body core to ambient, *i.e.* $R_{TEG-th} = R_{body} + R_{sink}$.

This fundamental trade-off and existence of an optimal R_{TEG-th} can be intuitively explained because decreasing the generator's cross sectional area increases the thermal resistance and thus will increase ΔT_{TEG}, which in turn increases the generator open circuit voltage. However decreasing a also increases the electrical resistance of the generator thus reducing its current drive capability. Under thermally matched

conditions, the maximum power that can be generated from a human powered thermoelectric generator can therefore be written as:

$$P_{max} = \frac{(n\alpha\Delta T)^2}{16R_{TEG-el}} \qquad (5)$$

where ΔT is the temperature difference between the body core and the ambient. In order to determine the limit of power generation we must rewrite Eqn. 5 as a function of the thermal resistance of the body and the heatsink with parameters chosen to give a thermal impedance match. This gives:

$$P_{max} = \frac{(\alpha\Delta T)^2}{16\rho K_{TEG}(R_{body}+R_{sink})} \qquad (6)$$

For typical temperatures of a human body to ambient generation scheme, bismouth telluride has a high value of $\alpha^2/(\rho K_{TEG})$ of around 0.0066 K^{-1} [15], giving a maximum power output of a thermoelectric generator of this material of around:

$$P_{max} = \frac{\Delta T^2}{2500(R_{body}+R_{sink})} \qquad (7)$$

which can be written as:

$$P_{max} = \frac{A\Delta T^2}{2500(R_{body-pa}+R_{sink-pa})} \qquad (8)$$

where A is the contact area of the generator and $R_{body-pa}$ and $R_{sink-pa}$ are the thermal resistances of a unit area of the body and heat sink respectively.

A minor additional complication to the calculation of the maximum power density of a thermoelectric generator is that the thermal resistance between the body core and the skin changes considerably with a change in human activity. At rest, the thermal resistance of the body is approximately 0.05 m^2K/W [12] whilst during heavy exercise it falls to less than 0.01 m^2K/W. The thermal resistance between the cold side of the thermoelectric generator and the air can be approximated from Chapter 5 of [16] as being approximately 0.05 m^2K/W. The thermal resistance of the thermoelectric generator should therefore be approximately 0.06 m^2K/W for a device optimised for a user when exercising and around 0.1 m^2K/W for a user at rest. For bismuth telluride, K_{TEG} is approximately 1.2 $Wm^{-1}K^{-1}$ meaning that the required height of the thermoelectric islands is h=1.2($R_{body-pa}+R_{sink-pa}$) which corresponds to 7 cm when the user is at rest or walking and 12 cm when the user is running. Whilst this configuration is optimal from the perspective of maximising power density, the aspect ratio achieved may not be realistic for all body-worn scenarios.

VI. COMPARISON

We are now in a position to compare the performance of the two main candidate types of encapsulable energy harvesting devices for wearing on or implanting into the human body using Eqns. 2 and 8. Comparisons are made against volume for both devices whilst the wearer is walking and running. Fig. 5 shows the limit of the performance of thermal and inertial kinetic energy generators on a running subject as a function of volume.

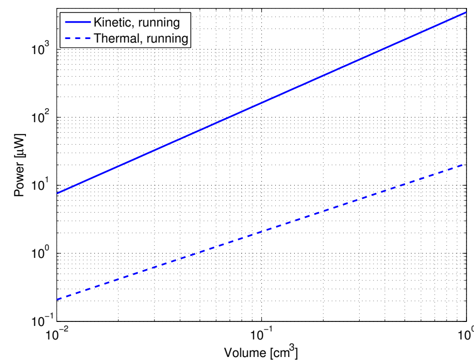

Fig. 5. Ultimate limit of the performance of thermal and inertial kinetic energy generators on a running subject

When walking, the same comparison is as shown in Fig. 6

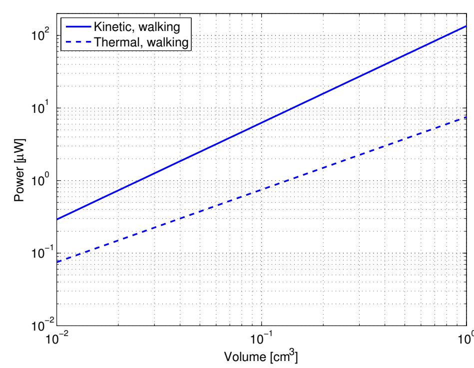

Fig. 6. Ultimate limit of the performance of thermal and inertial kinetic energy generators on a walking subject

As can be seen, the inertial kinetic device is superior in both cases and especially so when the user is running. Power densities of around 300 μW/cm^3 are theoretically achievable with kinetic energy harvesters compared to around 20 μW/cm^3 with a thermoelectric device. However, the analysis so far has not considered the difficulty of making such devices and how close the power density can be pushed to the theoretical limit. The current state of development of kinetic and thermal devices shows that the demonstrated thermal devices are achieving effectiveness values of around 70%, [14], whereas the best effectiveness for an inertial kinetic device is only around 1% [10]. Applying these scaling factors to the previous idealised analysis gives is useful in otrder to determine which of the generator types are suitable for use at the present state of development of such devices. Fig. 7 now shows that when running, the difference between the thermoelectric device performance and the inertial kinetic device is much less than in the idealised case, with the

thermoelectric device achieving greater power densities at small sizes. However, when walking, Fig. 8 shows that the thermoelectric device clearly superior.

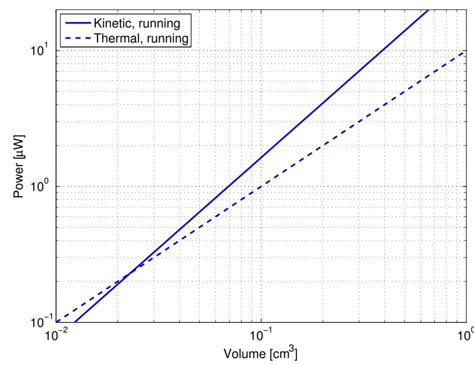

Fig. 7. Performance of thermal and inertial kinetic energy generators on a running subject with realistic device effectiveness

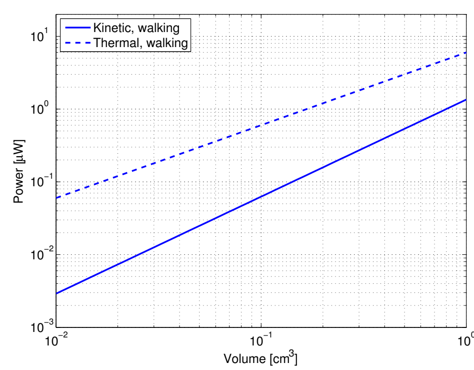

Fig. 8. Performance of thermal and inertial kinetic energy generators on a walking subject with realistic device effectiveness

VII. CONCLUSIONS

Motion-driven and thermoelectric devices are likely to be the main types of energy harvesting devices that can safely be used as hermetically-sealed power supplies for wireless implantable and wearable bio-sensors. Power densities of around 300 μW/cm^3 and 20 μW/cm^3 represent the ultimate limits for kinetic and thermal devices respectively whilst the user is running, and 30 μW/cm^3 and 10 μW/cm^3 are fundamental power density limits whilst the user is walking. However, in practice, thermal devices have been reported which are approaching these fundamental limits whilst kinetic energy harvesting devices are still achieving effectiveness values of around 1%. When these figures are taken into account, thermoelectric harvesters for human bio-sensors seem to be a sensible choice. Although low, these power densities should be able to provide sufficient power to be able to drive some tyoes of bio-sensor at low duty cycles.

One key barrier to obtaining the highest possible average power density from either thermal or kinetic energy devices harvesting from the human body is being able to achieve adaptability of the device characteristics. A kinetic device must be able to modify its resonant frequency and damping in order to operate at maximum power density as the wearer changes between walking and running and a thermoelectric device should ideally be able to alter its thermal resistance to operate effectively in the two scenarios. These features are difficult to achieve for both generator types and are an active area of research within the area of kinetic energy harvesters.

VIII. ACKNOWLEDGEMENTS

This work was supported in part by the Engineering and Physical Sciences Research Council (EPSRC) under grant number EP/G070180/1, “Next Generation Energy-Harvesting Electronics: Holistic Approach,” website: www.holistic.ecs.soton.ac.uk

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