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Wireless power transfer system for a human motion energy harvester

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ABSTRACT

Human motion energy harvesting as an alternative to battery powering in body worn and implanted devices is challenging during prolonged periods of inactivity. Even a buffer energy storage system will run out of power eventually if there is no external acceleration to the harvester. This paper presents a method to actuate the rotor inside a previously presented rotational piezoelectric energy harvester wirelessly via a magnetic reluctance coupling to an external driving rotor with one or more permanent magnet stacks attached. This makes it possible to recharge a battery or super-capacitor even if a patient is not moving. The use of a permanent magnet coupling has potential advantages compared to traditional inductive or ultrasonic methods, e.g. in terms of tissue damage and transmission depth. Simulation results show the achievable coupling torque for different configurations of magnet geometries and relative positions between the driving magnet stack(s) and the harvester. It is shown that using a single magnet stack yields better results than using two diametrically opposite stacks. Measurements are performed with different magnets, driving frequencies and orientations of the harvester. The results are discussed and successful energy transfer was achieved regardless of the orientation of the device with respect to gravity, which is desirable for real world applications. Lateral misalignment between the harvester and the driving magnet can also be overcome. The largest distance of power transfer reached was 32 mm with the largest magnets tested, and the optimal power output into a resistive load was over 100 μW at a frequency of 25 Hz. The functional volume of the harvester is 1.85 cm^3 – similar to the size of a wristwatch.

1. Introduction

The advent of more and more body mounted and implantable devices and sensors raises the question of how to sustainably provide power to them. Ubiquitous computing and body sensor networks, along with the internet of things, are major topics of discussion. Many technologies exist to make these a reality in terms of sensing and monitoring in healthcare as well as industrial settings. However, for truly powerful networks, large numbers of individual devices are required and the common bottleneck is the energy source. There are many applications where primary and secondary batteries are successful and appropriate. The constant need for recharging batteries in portable electronics is certainly a nuisance, but it is not a crucial drawback that hampers widespread adoption. Ultra-low-power electronics and communications can help mitigate the issue. It seems to be the case however that while many sensors, such as accelerometers in smart phones, are seeing increased energy efficiency, the addition of new sensors and communications drives the power consumption back up. Ultimately, efforts should be made on both ends of the scale, supply and demand, in order to find viable solutions.

Energy harvesting, the local generation of electricity from surrounding sources, is becoming an option for human body applications [1–5]. Especially in the case of implanted devices, a perpetual power source would be highly beneficial as it could extend the lifetime of implants and eliminate the need for intrusive surgery. In addition, a large number of failures in medical devices are caused by the batteries [6,7]. Suitable sources for human energy harvesting are temperature differences [8], photovoltaic systems [9,10] and glucose fuel cells [11]. Body motion is an abundant source of energy that can work for externally worn and implanted devices alike [12–14]. A good overview of the available solutions for powering medical devices can be found in [15]; Ref. [16] provides an introduction with a focus on piezoelectric devices and Ref. [17] is more specific to electromagnetic power generation.

One question that remains regarding all body mounted vibrational energy harvesting is what happens if the wearer does not move for extended periods of time, e.g. when bed-bound due to illness. It is realistic to assume that harvesters will have some form of backup or buffer energy storage, such as a super-capacitor or

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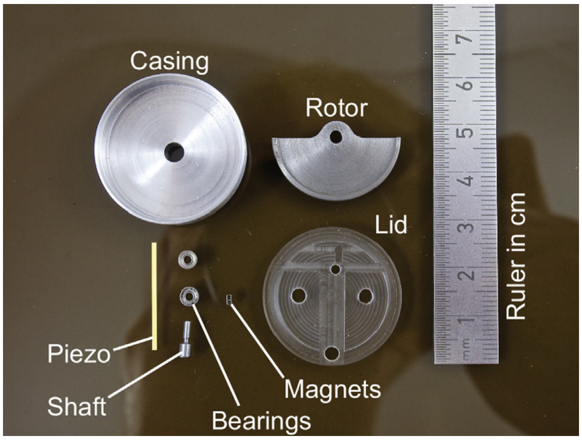

Fig. 1. Piezoelectric frequency up-converting rotational energy harvester components.

rechargeable battery, to overcome relatively short bouts of inactivity, for example at night during sleep. However, in cases of prolonged rest, there is a severe risk of the implant failing. Previously, the authors introduced a piezoelectric energy harvester for human body motion with a rotational proof mass [18]. Rotational harvesters are less dependent on their orientation with respect to gravity than linear devices where the proof mass can get stuck at an end stop. The device also employs the principle of frequency up-conversion through contact-less magnetic plucking of a piezoelectric beam. This technique, where the transducer always operates at its ideal frequency, has become popular for dealing with low frequency, random excitation. An electromagnetic version of such a mechanism was presented in [19]. Impact driven devices as in [20–23] bear the risk of damaging the brittle piezoelectric ceramic material in the long term. A more promising approach appears to be plucking via plectra [24–26]. The contact-less magnetic coupling chosen by the authors has also been employed by others [27].

The previously presented prototype operates similarly to a self-winding wristwatch and thus uses a proof mass close in dimensions to the rotor in a Seiko Kinetic watch [28]. It has been shown in [29] that an external driving magnet can latch on to the internal rotor of the device through a magnetic reluctance coupling. This adds the capability of externally actuating the harvesting mechanism and to generate electricity through use of a dedicated source in the absence of external excitation from motion. It is assumed that during normal operation, i.e. when a person is not bed bound, the power generated from inertial energy harvesting is sufficient to keep the system running and to trickle charge a buffer storage capacitor or battery. The addition of wireless charging capability provides a non-intrusive option of power delivery that significantly reduces the burden on a patient. This paper describes the wireless power transfer system and presents simulation and experimental results.

2. Magnetic reluctance coupling to the energy harvester

Fig. 1 shows the components of the harvester as it was introduced in [18]. Operating as a harvester, the semi-circular rotor can accept linear and rotational inertial excitation. As the rotor moves, a small permanent magnet swipes past a second permanent magnet that is attached to the tip of a piezoelectric bimorph beam. The repelling magnet force causes the beam tip to deflect up to the point where the beam force exceeds the magnetic forces and the beam is released to vibrate at its natural frequency. Given the high natural frequency of the beam, an up-conversion from the low input excitation frequency is thus achieved, rendering the transduction more efficient.

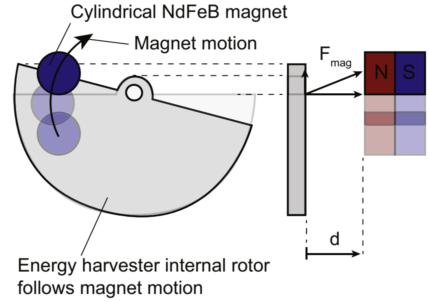

Fig. 2. Magnetic reluctance coupling of an external driving magnet to the internal harvester rotor.

The reluctance coupling to the internal rotor is illustrated in Fig. 2. The rotor is a half disc made of magnetic mild steel. The discontinuity at the edge of the half disc causes a change in reluctance when a permanent magnet is moved past it from the outside. The resulting magnetic force F_{mag} creates a torque that can be used to actuate the rotor during periods of rest, when no inertial forces on the rotor are present. The direction of polarisation of this driving permanent magnet is different from the one of the tip magnet on the beam. As a result, no significant adverse effects of the driving magnet onto the tip magnet were experienced during the measurements.

Wireless RF energy harvesting and power transfer, as described in [30–32], differ by the fact that harvesting utilises ambient RF energy, while transfer employs a dedicated source. The latter is the case for the device presented in this paper. Human body applications requiring wireless power transfer often use inductive or ultrasonic coupling [33,34,15,35]. Potential drawbacks of inductive coupling are safety concerns due to the high power high frequency fields, and increasing tissue attenuation at higher frequencies which limits the penetration depth [36]. This is the reason why electrodynamic receivers have been investigated. The principle relies on coupling the magnetic field from a transmitter coil to a permanent magnet in a receiver at a distance. The resulting motion of the permanent magnet then induces a current in a surrounding coil, rather than the coil picking up the magnetic field from the transmitter directly [37–40]. Another variant of this principle uses a rotating magnet receiver [41].

The system in this paper is different in that it uses a magnetic reluctance coupling, where a permanent magnet couples on to a semi-circular steel rotor. Permanent magnetic torque couplings or gears in general have the advantage that no lubrication is required and that they can transfer torque where a separation of media is needed [42–44]. They are used in applications such as waste water pumps. Through-wall transmission using alternating magnetic fields has been demonstrated [45]. One device for powering a pacemaker that uses permanent magnetic coupling in a similar way to this work is introduced in [46,47]. The differences are that an electromagnetic transduction mechanism is used instead of a piezoelectric one and that the device in itself can not function as a standalone energy harvester. In addition, due to the specific arrangement of the coupling and the transduction mechanism it was shown that the magnetic field from the coupling negatively affected the transduction.

3. Steady state simulation of the achievable coupling torque

In order to better understand the coupling of an external magnet to the rotor, a series of Comsol 5.0 FEM simulations was performed.