Wireless Energy Transfer Through Magnetic Reluctance Coupling

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Abstract.
Energy harvesting from human motion for body worn or implanted devices faces the problem of the wearer being still, e.g. while asleep. Especially for medical devices this can become an issue if a patient is bed-bound for prolonged periods of time and the internal battery of a harvesting system is not recharged. This article introduces a mechanism for wireless energy transfer based on a previously presented energy harvesting device. The internal rotor of the energy harvester is made of mild steel and can be actuated through a magnetic reluctance coupling to an external motor. The internal piezoelectric transducer is consequently actuated and generates electricity. This paper successfully demonstrates energy transfer over a distance of 16 mm in air and an achieved power output of 85 µW at 25 Hz. The device functional volume is 1.85 cm³. Furthermore, it was demonstrated that increasing the driving frequency beyond 25 Hz did not yield a further increase in power output. Future research will focus on improving the reluctance coupling, e.g. by investigating the use of multiple or stronger magnets, in order to increase transmission distance.

1. Introduction
Previously, the author presented a rotational energy harvester for human motion based on piezoelectric beam plucking [1]. Energy harvesting for body worn and implantable devices is an attractive alternative to battery powering. It can alleviate the maintenance burden and potentially eliminate the need for repeated intrusive surgery. The above-mentioned rotational energy harvester has the capability to harvest energy from low frequency motion efficiently through piezoelectric frequency up-conversion. The rotational layout of the design makes it less dependent on gravity an through the eccentric proof mass it can accept excitation in two linear and rotational directions. Figure 1 shows the different components of the harvester.

However, especially in medical applications, there is an ultimate question of what happens if a patient becomes bed-bound. This is a likely scenario and the challenge is to avoid failure of vital implants due to the energy harvester not generating any electricity at rest. Compared to thermoelectric harvesters or glucose fuel cells, this is a problem that all motion-based devices for medical applications are facing. This article demonstrates external actuation of the rotational harvester through a magnetic reluctance coupling without any changes to the initial prototype. Energy is provided by a dedicated source, in this case an electric motor, and transferred trough the magnetic coupling onto the rotor inside the harvester. This means that there is a wireless energy transfer between the source and the receiver (the harvester). The same device can thus

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be used for wireless energy transfer with a dedicated source and for energy harvesting and an internal battery could be charged even in the absence of an external vibration.

Typically, power transfer into the human body is performed via an inductive or ultrasonic coupling [2,3]. The novelty of this system is illustrated in figure 2. An external magnet mounted on a DC motor rotates at a distance from the micro generator. The rotor on the inside is a half disc made of magnetic mild steel. The reluctance change as the permanent magnet passes the edge of the rotor causes the rotor to latch on to the magnet and follow its rotation. The transduction mechanism is the same as for the operation as a harvester – a small permanent magnet fixed to the rotor actuates a piezoelectric beam with a second magnet on its tip each time the two pass each other.

Power transfer using permanent magnet coupling is not a novel concept as described in [4]. However, applications for the human body are little investigated. In [5] such a device is presented but the coupling magnets had a negative effect on the electromagnetic transduction mechanism. This problem does not occur in this device due to the piezoelectric transduction. In addition, the combined operation of a device as energy harvester for the general case and as a receiver for wireless energy transfer in times of need makes this a highly versatile prototype. The experimental results presented are specific to the latter case as the energy harvester operation has been shown previously.

2. Experimental Set-Up

Figure 3 depicts the experimental set-up used. The rotational energy harvester, operated as a micro-generator in this case, is held in a vertical position in a 3D-printed holder. Opposite, a DC motor is held in a similar fixture with a disc carrying permanent magnets (NdFeB disks $1/4'' \times 1/8''$). The DC motor is driven by an adjustable power supply in order to vary the rotational frequency. Both mounts are adjustable, the left one allows the gap $d$ between the generator and the permanent magnets to be changed and the right one provides lateral displacement $L$ to investigate misalignment between the generator and the DC motor. The piezoelectric beam inside the generator is directly connected to an impedance matched resistive load of 150 kΩ. The power output is then established by measuring the root-mean-squared voltage drop across the resistor three times in a row over a time of 10 s and taking the average.

Figure 1 already shows the components of the energy harvester. The internal series bimorph piezoelectric beam has a free length of 19.5 mm, width of 1 mm and total thickness is 0.37 mm.
The diameter of the casing is 30 mm and the functional volume without the casing is 1.85 cm$^3$. The total weight is 10.5 g

![Figure 3: Experimental set-up](image)

3. Results

Figure 4 shows the power output in relation to the distance $d$. The experiments are started at an initial distance of 1 mm which is progressively increased until the reluctance coupling is too weak to keep rotating the internal rotor. This happened at a maximum distance of 16 mm. The driving frequency from the DC motor was set to 10 Hz. Due to the design of the device, the power output is dependent on the driving frequency. An increased number of actuations of the internal piezoelectric beam results in an increase in power. This is why the power output stays relatively stable around 45 $\mu$W as long as the rotor keeps following the external magnet. The variations that can be seen at the smaller distances $d$ might be caused by inconsistencies in the DC motor driving frequency. It was found that, at close proximity to the aluminium casing of the generator, Eddy currents induced by the permanent magnets can affect the driving motor. A future solution to this problem would be to use a stepper motor in order to achieve a more consistent rotation. Figure 5 shows the corresponding voltage output of the piezoelectric beam. It matches the expected behaviour from the operation as a harvester. The ring down of the beam vibration after each actuation is clearly visible.

The power output in respect to the motor rotational frequency is depicted in figure 6 at a constant distance $d = 1$ mm. As previously mentioned, higher frequencies translate to more frequent actuations of the piezoelectric beam and thus increased output. However, after about 25 Hz, the previous excitation has not fully rung down before the next actuation happens. This causes a weaker coupling between the internal magnets and explains the drop in output power beyond this point. This is further supported by figure 7, which shows the voltage output at 30 Hz being significantly lower than in figure 5. This is an interesting result as it shows that there is a limit after which it is disadvantageous to further increase the frequency. The maximum power transfer achieved was 85 $\mu$W.

Finally, the design can cope with a lateral misalignment $L$ to a certain degree as depicted in figure 8. At a separation of $d = 1$ mm and at 10 Hz, the DC motor is displaced in 1 mm steps. Occasionally, the rotor fails to keep up with the driving magnet before latching on again. Figure 9, showing the corresponding voltage output at $L = 4$ mm, confirms an irregular actuation pattern. This explains the slightly lower power output and larger error bars with an increase in misalignment.
Figure 4: Power output in relation to separation distance $d$ between motor and harvester, incl. error bars

Figure 5: Voltage output at 10 Hz, $d = 1$ mm and 150 kΩ impedance matched resistive load

Figure 6: Power output in relation to motor driving frequency at $d = 1$ mm, error bars are insignificantly small

Figure 7: Output voltage waveform at $d = 1$ mm and 30 Hz driving frequency

4. Conclusions

This paper demonstrates a mechanism for wireless energy transfer with a dedicated source to enhance the versatility of a previously demonstrated motion energy harvester. The device can be operated as a piezoelectric rotational energy harvester most of the time. However, in cases without external motion, e.g. the wearer being bed-bound for prolonged periods of time, the internal rotor of the device can be actuated through a magnetic reluctance coupling with an external permanent magnet driven by a DC or stepper motor. This makes it possible to recharge an internal battery and prevent the failure of sensors otherwise powered only when actively harvesting energy.

A novel aspect of the coupling is that it uses a permanent magnet latching onto mild steel, whereas other methods use ultrasonic or inductive coupling. A potential advantage might be reduced tissue damage and deeper penetration since a stronger coupling can be achieved by choosing a larger, stronger mechanism. This will be investigated in the future.

The energy transfer was successful over a distance of up to 16 mm and a maximum power transfer of 85 µW was achieved at a driving frequency of 25 Hz. Further increasing the driving
frequency did not yield any more power as the actuations of the piezoelectric transducer became too closely spaced to allow a full ring down after initial deflection and release. Furthermore, it was demonstrated that the mechanism is relatively robust against lateral misalignment, showing a 25 % drop in power output for a 4 mm shift between the rotational axes of the harvester and the DC motor.

Future research will improve the consistency of the driving frequency by replacing the DC motor with a stepper motor and better controller. The reluctance coupling between the rotor and permanent driving magnet will be investigated in order to find the best combination. For instance, using multiple or stronger magnets could improve the coupling strength. Ultimately, it will be interesting to perform experiments regarding penetration through different media. This could extend the scope of the mechanism to other applications such as energy transfer in harsh environments or through water/gas pipe walls.

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