Development of a Miniature Water Turbine Powered by Human Weight During Walking

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Abstract. Energy harvesting systems as an autonomous power supply for interconnected wearable devices have become increasingly important. The unobtrusive integration into clothing poses a great challenge to the feasible application of these harvesting devices. For systems worn on the lower body, a shoe-based energy harvester may offer the solution since the shoe offers a protected building space. This work presents the development of a water turbine system, which uses the human weight to cause water flows within the turbine. One reservoir (68 x 60 x 18 mm³) is attached on either side of the turbine (58 x 54 x 16 mm³). In a laboratory, the energy generated during one actuation of a reservoir was 3 mJ. During normal walking, with two separate systems, energies of 2.27 mJ and 2.26 mJ per step were achieved at a walking speed of roughly 4 km/h.

1. Introduction
The idea of powering body-worn sensor systems and devices with the energy expended by the human body is not new and is being investigated by several research groups around the world. Devices that harvest the kinetic energy of human motion have been presented in many varieties and different transduction mechanisms. Exemplary devices that use the swing motion of the leg as an energy source [1, 2] or the shock upon impact of the foot with the ground [3] can generate an average power of a few milli-Watts. Harvesting devices that use the force that acts on the shoe due to the weight of the user, either transduce the vertical motion directly, e.g. by using piezoelectric material [4], or translate the vertical motion into horizontal or rotational motion because of the limited height of the shoe sole. One possibility of translating the downward motion of the foot into a different type of motion is to use fluidic reservoirs or “cushions”. A reservoir can be placed underneath the heel and another under the forefoot. When the heel touches down and compresses the back reservoir, the fluid is pushed from the back of the shoe towards the front and vice versa as the weight shifts from the back to the front of the shoe. The fluid flow can then be used to drive the actual transduction mechanism. In [5] the fluid flow drives a differential piston which in turn drives gears and a generator to generate power outputs up to 800 mW. This work presents such a fluidic system. However, the present setup consists of a limited number of mechanical components to allow miniaturization, i.e. the fluid directly drives a turbine without gears.

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2. Fabrication

The device consists mostly of 3D-printed components. The turbine wheel contains an axially polarized magnet with four magnet poles. A picture of the components as well as a schematic diagram are given in Figure 1. The coils were taken from a flat Faulhaber DC motor (type 2607T012SR). Three coils are placed at 120° phase shifts in a printed holder which also seals off the fluid-filled turbine compartment from the rest of the device. One of these coil holders is placed on either side of the main housing. A PCB board is added to the bottom holder to wire the three bottom coils in a star connection. The top coils are placed directly opposite the bottom coils and connected in opposite series to simultaneously create an induced voltage. The turbine body has a total size of 58 x 54 x 16 mm³.

![Figure 1. (a) Components of the water turbine. The main housing with the fluidic channels and the coil holders were 3D-printed. (b) Schematic showing the different layers of the turbine system.](image)

Cylindrical pins are used to connect the two PCB boards. The fluid reservoirs are fabricated from shrinkage tube pieces of 50 mm length, which is very thin (0.4 mm walls) while being very robust as it has no seams. On either end, the tube is closed off with 3D-printed components resulting in a total size of 68 x 60 x 18 mm³. A bracket is placed over each reservoir in order to apply the weight of the test person uniformly on the shrinkage tube. Figure 2 shows the built device with fluidic channels embedded within the printed material in (a).

![Figure 2. (a) Close-up of the built turbine and the fluid reservoir. The fluidic channels can be seen through the semi-transparent 3D-printed housing. (b) Laboratory test setup with a “Zwick-Roell” testing machine which can exert a force at a controlled speed.](image)

The biggest problem during testing of this device was to properly seal the fluid reservoirs. The largest walked distance without leaking was about 200 m. As part of ongoing work, an improved seal is being developed. Also experiments are being conducted to find the optimal volume of water to be used in the system.
3. Experimental Data

3.1. Laboratory Experiments
In Figure 2(b) the laboratory setup is shown, where a testing machine is used to compress the fluidic reservoir at defined speeds for a given distance. Because a single actuation can be performed, this can only mimic one part of a human step. The velocity of the testing machine was set to 10 mm/s for a total deformation of 5 mm. The recorded force generated under these actuation conditions reached up to $\approx 260$ N. A varying ohmic load was attached to a three-phase rectifier based on the power-management in [6]. Table 1 shows the results. A maximum of 3 mJ could be generated for a single actuation. Variations were caused by the uncertainty in the exact amount of water in the reservoir at the start of each measurement.

Table 1. Generated energy for varying electrical loads and a single actuation of the fluid reservoir in a laboratory experiment.

| Load [Ω] | 40  | 45  | 50  | 55  | 60  | 65  | 70  | 75  | 80  | 85  | 90  | 100 | 105 | 110 | 115 |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Energy [mJ] | 2.29 | 2.6 | 2.45 | 2.67 | 2.84 | 2.95 | 2.74 | 2.99 | 2.75 | 2.99 | 3.04 | 2.95 | 2.99 | 2.99 | 1.89 | 0.83 |

3.2. Real-Life Walking experiments
The complete device was placed within a sandal between the rubber sole and the cork insole for easy access as shown in Figure 3. Additional 3D-printed pieces were added to keep the turbine in place. In the future, a customized sole could contain dedicated compartments to fit the system.

Figure 3. (a) Full turbine system with two fluid reservoirs. (b) Placement of the turbine in a sandal (underneath the insole) for easier access during testing.

Testing was done on level ground at a normal walking speed of roughly 4 km/h, with a test person weighing approximately 70 kg. The rectified voltages measured across an ohmic load of 100 ohms for two separate turbine systems are shown in Figure 4. A 47 µF smoothing capacitor was used in both cases.

Each step contains two distinct voltage peaks that represent the two phases during stance where most of the body weighs on the heel or on the forefoot. In between the peaks, the voltage drops as the weight is balanced across the foot. The fluidic channels of the turbine are placed in such a way, that the turbine always turns in the same direction, hence the voltage only drops to zero very briefly during the swing phase of the foot, when no force acts on the fluid reservoirs.

The voltage peaks at 1 V (the resistance of each coil is 18 ohms). The corresponding instantaneous power output reaches up to 10 mW. For the two datasets of fifteen seconds each as shown in Figure 4, the generated energy is 24.94 mJ and 22.63 mJ for a total of 11 and 10 steps respectively. The energy per step thus amounts to approximately 2.3 mJ for either device. Considering the time span of 15 seconds, this translates into average power outputs of 1.66 mW and 1.51 mW.
Figure 4. Rectified voltage output measured across an ohmic load of 100 ohms (using a 47 µF smoothing capacitor) for two separate turbine systems in (a) and (b).

4. Conclusion

The main issue with this device was the water sealing. After a few tens of meters, the reservoirs started leaking and when heavier test persons walked with the device, the shrinkage tube would slip out of the sealing mechanism due to the large forces exerted by the fluid. An improved seal is currently in development. Another solution may be to gradually reduce the amount of fluid in the system until the pressure build-up can be handled by the seal. The effects of this on the power output have to be investigated.

In terms of wearing comfort, there was no negative effect due to the turbine, other than the increased height of the shoe sole which had to accommodate the system and its maximum height of 18 mm. From a subjective point of view, the shoe felt very comfortable.

This device setup was able to generate average power outputs of roughly 1.6 mW or an energy of 2.3 mJ per step while walking. It contains only one moving part and thus is less noisy and prone to mechanical failure as other systems. Due to the lack of mechanical gears, the large forces cannot be translated into large speeds and thus the power output is significantly lower than for example in [5]. The presented device however is far smaller than the device in [5] and can actually be integrated in a shoe sole. Future work includes introducing a mechanical transmission while retaining the compactness of the device.

5. References

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