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Energy Autonomous Wireless Sensing System Enabled by Energy Generated during Human Walking

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Abstract. Recently, there has been a huge amount of work devoted to wearable energy harvesting (WEH) in a bid to establish energy autonomous wireless sensing systems for a range of health monitoring applications. However, limited work has been performed to implement and test such systems in real-world settings. This paper reports the development and real-world characterisation of a magnetically plucked wearable knee-joint energy harvester (Mag-WKEH) powered wireless sensing system, which integrates our latest research progresses in WEH, power conditioning and wireless sensing to achieve high energy efficiency. Experimental results demonstrate that with walking speeds of 3~7 km/h, the Mag-WKEH generates average power of 1.9~4.5 mW with unnoticeable impact on the wearer and is able to power the wireless sensor node (WSN) with three sensors to work at duty cycles of 6.6%~13%. In each active period of 2 s, the WSN is able to measure and transmit 482 readings to the base station.

1. Introduction

Wearable energy harvesting (WEH), which scavenges energy around human body and converts it to electric energy, has been the subject of scientific and technological effort worldwide in the past two decades [1]. This has been driven by the demand to prolong the life time and reduce the maintenance of body sensors, which are increasingly used for human health condition monitoring to support diagnosis and improve treatment from a medical point of view [2]. Those sensors are currently powered by batteries with limited capacity and thus limited life time but are usually required to operate in long-term. WEH has been considered as a potential technology to provide sustainable electric power supply for those sensors to extend the life time of or fully replace the batteries to establish energy autonomous wireless sensing systems.

Although there are variable energy sources such as solar illumination, radio-frequency energy and thermal energy available around human body, WEH from kinetic energy has attracted the most attention due to the large amount of energy available during human motion and has been implemented by using piezoelectric, electromagnetic and electrostatic mechanisms [3]. To date, a large amount of wearable energy harvesters have been proposed. However, most of these harvesters were tested under simulated input excitations, and limited research has been devoted to integrating them with wireless sensors and testing them in system-level under real world settings so as to advance the technology towards application.

In previous work [4], the present authors developed a magnetically plucked knee-joint energy harvester (Mag-KEH), which is able to generate an average power of 5.8 mW when actuated by simulated knee-joint motion at 0.9 Hz. In this work, the Mag-KEH was modified to a wearable prototype and integrated with a wireless sensor node to establish a magnetically plucked wearable energy harvester (Mag-WKEH) powered wireless system. The performance of the system, including the power



generation, the capability of the wireless sensing and transmission, has been characterized as a human subject carrying the system walks at different speeds.

2. Description of the Mag-WKEH powered wireless sensing system

The Mag-WKEH powered wireless sensing system is shown in Figure 1. The whole system is fixed to the leg through an upper brace and a lower brace. Two circuits are fixed on the top of the Mag-WKEH: one is a rectifying circuit, and the other is a circuit comprising a power management module (PMM), an energy aware interface (EAI) and a wireless sensor node (WSN).

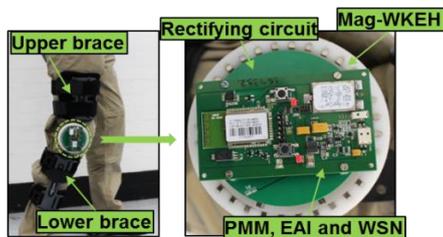


Figure 1 The magnetically plucked wearable knee-joint energy harvester powered wireless sensing system

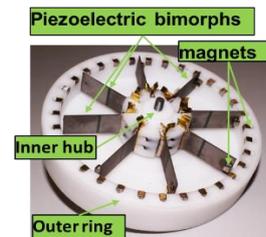


Figure 2 The magnetically plucked wearable knee-joint energy harvester

The Mag-WKEH, shown in Figure 2, used in this study is a wearable version of the Mag-KEH developed in [4]. Compared with the Mag-KEH, which was designed to test on a stepping motor, the Mag-WKEH was designed with adapters to connect to the lower and upper braces. The Mag-WKEH comprises eight piezoelectric bimorphs fixed on an inner hub. Each bimorph tip was glued with a permanent magnet. Thirty two permanent magnets were equally positioned along the inner edge of the outer ring. The inner hub was connected to the lower brace, while the outer ring was connected to the upper brace. As the knee-joint motion actuates the relative rotation between the inner hub and the outer ring through the two braces, the piezoelectric bimorphs are plucked by the intermittent magnetic forces, i.e. they are first deflected and then released to free vibration at their resonance frequency. The plucking mechanism converts the low frequency knee joint motion to the high resonant vibration of the piezoelectric bimorphs, thus achieving high power generation. More details of the dynamic responses of the magnetically plucked piezoelectric bimorphs can be found elsewhere [4]. The Mag-WKEH has a diameter of 90 mm and height of 25 mm. The total weigh is 300 g excluding the braces.

A schematic of the system is presented in Figure 3. The energy generated by the Mag-KEH is rectified and then processed by the PMM. The rectifier circuit comprises eight full-bridge rectifiers. Each bimorph was connected to a rectifier individually and the outputs of the eight rectifiers were connected in parallel and then to the PMM. The output of the PMM charges a 10 mF storage capacitor C_{CS} and the energy stored in C_{CS} is used to power the WSN under the supervision of the EAI.

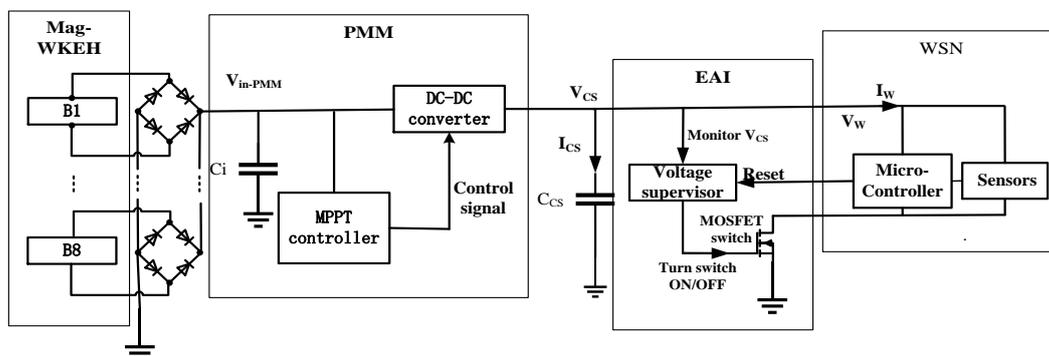


Figure 3 A schematic of the wearable knee-joint energy harvester powered wireless sensing system

The PMM was designed with maximum power point tracking (MPPT) function to address the low power transfer efficiency resulted from the electric impedance mismatch between the Mag-WKEH and

the succeeding circuits. Initially, the DC-DC converter is disabled and the smoothing capacitor C_i is charged up by the Mag-WKEH. As the voltage across C_i , which is V_{in-PMM} , increases to half of the open circuit voltage V_{OC} of the Mag-WKEH, the DC-DC converter is enabled by the MPPT controller and the energy stored in C_i is transferred to C_{CS} . As V_{in-PMM} drops to below $V_{OC}/2$, the MPPT controller disables the DC-DC converter. C_i is charged up again and the cycle is repeated. More details of the design and implementation of the MPPT controller can be found in [5].

The energy aware interface (EAI) uses a voltage supervisor to monitor the voltage V_{CS} across the storage capacitor C_{CS} . When V_{CS} increases to be higher than V_1 (3.15 V), the voltage supervisor turns on the MOSFET switch and the energy stored in C_{CS} is discharged to the WSN, which is then turned to its active mode to measure and transmit data. When V_{CS} decreases to be lower than V_0 (determined by the WSN) due to the discharge, the WSN finishes its tasks and then reset the MOSFET switch. As a result, C_{CS} is disconnected to the WSN and the WSN is turned to its sleeping mode.

The WSN uses a JN5148 microcontroller unit (MCU) to coordinate the wireless transmission and data sampling from three sensors: an ADXL 335 3-axis accelerometer, a MCP9700 temperature sensor and a humidity sensor. In each active phase, the MCU takes one reading from the temperature sensor and the humidity sensor one by one. Then it takes 3 readings from the 3-axis accelerometer every 10 ms. Each time after 48 readings have been taken, the MCU measures V_{CS} to judge whether the energy in the C_{CS} is enough to take another 48 readings and transmit all the data before V_{CS} drops to too low (<2.45 V) for the operation of the WSN. If so, the MCU will take another 48 readings and the cycles repeat. If not, the MCU will turn on the transceiver, transmit all the data to the base station, and then reset the voltage supervisor in the EAI to turn off the MOSFET switch.

3. Experimental Methods

Experiments were performed with a human subject wearing the Mag-WKEH powered wireless sensing system and walking on a treadmill at speeds ranging from 3 to 7 km/h. A base station was placed at a distance of 4 m and connected with a laptop, which was used to monitor the data received by the base station. The voltages and currents input to the PMM, the storage capacitor C_{CS} and the WSN (denoted in Figure 3) were recorded to calculate the electric energy and power generated or consumed.

4. Results and Discussions

Figure 4 shows the average power output of the Mag-WEKH at different walking speeds, which is the sum of the power input to the PMM and the power lost in the rectifying circuit. As the walking speed increases from 3 to 7 km/h, the power output grows from 1.9 to 4.5 mW. The expected increase of the power with the walking speed is attributed to the more frequently and more quickly plucking of the piezoelectric bimorphs at higher walking speeds.

Figure 5 shows the voltage across and the current through C_{CS} and the WSN at a walking speed of 4 km/h. In phase (1), C_{CS} is charged up by the Mag-WKEH and its voltage V_{CS} increases steadily from zero to 3.15 V. In this phase, V_w and I_w are zero because the EAI disconnects the WSN to C_{CS} and the WSN is at its sleeping mode. The time period of phase (1) is referred to as cold start time t_c , which is 62.2 s in this case. In phase (2), the EAI turns on the switch. As a result, the energy stored in C_{CS} is discharged to the WSN. The WSN is switched to its active mode to measure data from the three sensors at a sampling frequency of 100 Hz. Because the power consumption of the WSN is higher than the charging power provided by the Mag-WKEH, V_{CS} decreases during phase (2). Before V_{CS} decreases to be too low (<2.45 V) to operate the WSN, the WSN transmits all the measured data to the base station and then resets the EAI to turn off the switch and consequently disconnect the WSN to the C_{CS} , after which phase (3) starts. In phase (3), the WSN is turned to its sleeping mode again and C_{CS} is charged up by the Mag-WKEH. As soon as V_{CS} increases to 3.15 V, the EAI turns on the switch and another phase (2) starts. The cycles are then repeated. The time period of phase (3) is referred to as warm start time t_w . Each active mode of the WSN (phase (2)) lasted 2 s (referred to as active time t_a), during which 482 readings were sampled from the sensors (1 from the temperature sensor, 1 from the humidity sensor and 480 from the 3-axis accelerometer) and successfully received by the base station.

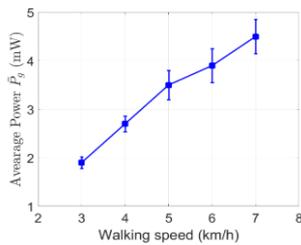


Figure 4 Average power output of the Mag-WKEH at different walking speeds

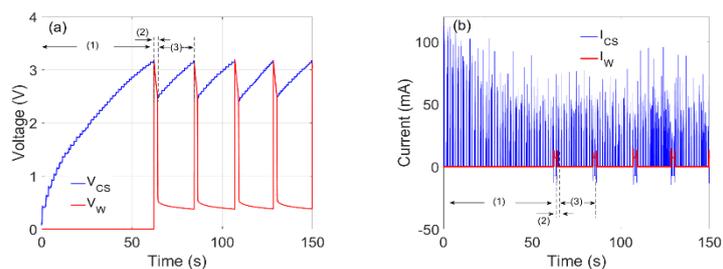


Figure 5 Voltage (a) across and current (b) through the storage capacitor and the wireless sensor node at walking speed of 4 km/h

The cold start time t_c , the warm start time t_w and the duty cycle of the system at different walking speeds are presented in Figure 6(a), (b) and (c), respectively, where the duty cycle is calculated as $t_a/(t_a + t_w)$. As the walking speed increases, both t_c and t_w decreases. This is because the power output of the Mag-WKEH increases with the walking speed. As a result, both the time required to charge the C_{CS} from zero to 3.15 V, i.e. the cold start time, and the time required to recharge the C_{CS} to 3.15 V in phase (3), i.e. the warm start time, are reduced. It should be noted that the active time t_a of the WSN keeps almost constant at different speeds because it is mainly determined by the capacitance of the C_{CS} . Because of the decrease of t_w , the duty cycle increases with the walking speeds.

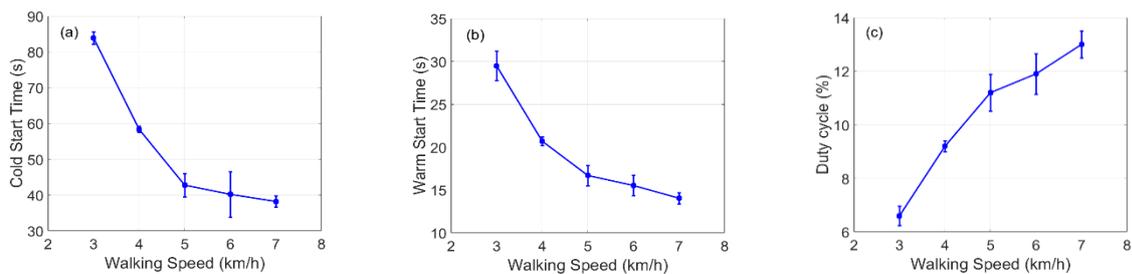


Figure 6 Cold start time (a), warm start time (b) and the duty cycle of the system at different walking speeds

5. Conclusions

This paper reported the implementation and characterisation of the Mag-WKEH powered wireless sensing system enabled energy generated during human walking. The power output of the Mag-WKEH was measured at different walking speeds and its capability to power the wireless sensor node through the power management circuit and energy aware interface was tested. At all the walking speeds tested (3~7 km/h), the Mag-WKEH is able to produce enough energy to power the wireless sensor node to measure and transmit data with a working duty cycle up to 13% while imposing unnoticeable reactive impact on the wearer. With proper sensors deployed in the WSN, the developed system can be potentially used for long-term body/health condition monitoring.

Acknowledgment

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