Energy harvesting during human walking to power a wireless sensor node

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A B S T R A C T
The continuous progress made in wearable energy harvesting technology is delivering sophisticated devices with increasing power outputs, which are possible to provide sustainable energy supply for body sensors to achieve energy-autonomous wireless sensing systems. This paper reports the development and characterisation of a wearable energy harvesting powered wireless sensing system with system-level strategies to address the challenges in energy harvesting, power conditioning, wireless sensing and their integration into a system. The system comprises four parts: (1) a magnetically plucked wearable knee-joint energy harvester (Mag-WKEH) to scavenge energy from knee-joint motions during human walking, (2) a power management module (PMM) with a maximum power point tracking (MPPT) function, (3) an energy-aware interface (EAI) for dealing with the mismatch between the energy generated and demanded, and (4) an energy-aware wireless sensor node (WSN) for data sensing and transmitting. Experiments were performed with a human subject wearing the system and walking on a treadmill at different speeds. The experimental results showed that as the walking speed increased from 3 to 7 km/h, the power output of the Mag-WKEH increased from 1.9 ± 0.12 to 4.5 ± 0.35 mW, and the generated power was able to power the WSN to work at duty cycles from 6.6 ± 0.36% to 13 ± 0.5% with an active time of 2.0 ± 0.1s. In each active time, the WSN was able to sample 482 readings with an interval of 10 ms from the sensors and transmit all data to a base station at a distance of 4 m.

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1. Introduction

Long-term monitoring of body conditions such as vital signs, daily activities and gait patterns by using wireless body sensors is highly desirable from a medical point of view to support diagnosis and improve treatment [1,2]. A crucial issue for body sensors to perform such monitoring is the power supply. Current body sensors are powered by large and relatively bulky batteries, which usually have a limited lifetime, while the ultimate vision of body sensors is expected to operate reliably for a duration of months or years rather than hours or days [3]. Re-charging or replacing depleted batteries can extend the lifetime of the body sensors; however, the maintenance can be a problem when a large number of sensors are involved or when the sensors are placed inside the human body.

One promising solution to this issue is wearable energy harvesting, which converts the energy around human bodies to usable electric energy to provide a power supply for the body sensors so as to establish an energy-autonomous wireless sensing solution. The energy sources available include solar illumination, radio-frequency energy, thermal energy and kinetic energy from human motions [4]. Among these sources, kinetic energy harvesting has attracted a great deal of interest due to the large amount of energy available during human movement [5], and has been intensively investigated by using various transduction mechanisms including electromagnetic, electrostatic and piezoelectric in the past two decades [6–8]. The electric power output of these wearable energy harvesters varies from tens of microwatts to as high as several watts, highly depending on the energy sources and the size of the energy harvesters.

With the increasing electric power output delivered by the wearable energy harvesters and also with the continuous progress made in low power-consumption sensing technology, it is technically feasible to build wearable energy harvesting powered wireless sensing systems. However, compared with the large number of studies on the energy harvesting devices, the research devoted to the implementations of energy harvesting powered wireless sens-
ing systems is limited. In one of the earliest reports on this topic, Shenck et al. [9] used a piezoelectric energy harvester embedded in a shoe to power an active radio frequency (RF) tag, which was able to transmit a 12-bit wireless identification code every 3–5 steps. More recently, Zhao et al. [10] developed polyvinylidene difluoride (PVDF) based energy harvester embedded in a shoe insole, which was successfully used to power a wireless transmitter. Kuang et al. [11] developed a mechanically plucked energy harvester actuated by simulated knee-joint motion to power a WSN and achieved a duty cycle of 3.5%. There are a few studies on wireless sensors powered by kinetic energy harvesting from ambient vibrations (other than human motions) [9,12–16]. For example, Roundy et al. [12] designed piezoelectric cantilever generator driven by vibrations at 120 Hz to power a radio transmitter and achieved a duty cycle of 1.6%. Reilly et al. [14] developed a trapezoidal piezoelectric generator driven by vibrations at 100 Hz to power a WSN with a three-axis accelerometer and achieved a duty cycle of 0.2%. The first limitation with some of these studies is that the energy harvesters were actuated at high frequencies (60–180 Hz) to achieve high power output [12,14,15]. However, these high-frequency vibrations are not usually available in practice, particularly in the human bodies. Secondly, lots of these studies employ a direct charging method or switched capacitors (as categorised by Chao [17]) as the interface between the energy harvester and the WSN [9,12,14,16,18], which leads to low power transfer efficiency. Thirdly, still a high number studies focused on radio-frequency transmitter design without sensing function [10,12,16].

In this work, a wearable energy harvesting powered wireless sensing system has been developed and characterised. This system integrates our latest research work to address the challenges in the wearable energy harvesting, power conditioning and wireless sensing: (1) a Mag-WKEH has been developed and prototyped to increase the power output and lifetime; (2) a novel PMM with MPPT has been designed to increase power transfer efficiency of the Mag-WKEH and thus increase the energy available for the energy storage and the WSN; and (3) an energy-aware WSN has been developed to achieve a long active time with the ability to measure and transmit a large number of data at high energy efficiency. The power generation of the Mag-WKEH, its capability to power the WSN, and the energy distribution in the system are characterised.

2. Mag-WKEH powered WSN: system design

Fig. 1 shows the block diagram of the Mag-WKEH powering a WSN. It comprises four modules: the Mag-WKEH with eight PZT bimorphs (B1–B8), a PMM with a MPPT function, an EAI and a WSN with a base station (not shown) placed at a distance of 4 m. The AC outputs from the eight bimorphs of the Mag-WKEH were rectified and then connected to the PMM. A 22 mF aluminium electrolytic storage capacitor (denoted as $C_S$) was used to store the energy output from the PMM.

2.1. Mag-WKEH

2.1.1. Magnetic plucking mechanism

The magnetic plucking mechanism is a frequency up-conversion strategy previously explored by the present authors [19] and other researchers [20,21] from different aspects. It uses a magnetic force to deflect a piezoelectric cantilever, which is then released to vibrate freely at its resonance frequency. In this way, the high-frequency resonant vibration of the piezoelectric cantilever can be excited even when the input vibration is at low frequencies. Because piezoelectric energy harvesters operate at the maximal efficiency when actuated at their resonance frequency, this mechanism improves the energy conversation efficiency and the generated electrical power output. The magnetic plucking mechanism is particularly beneficial for wearable energy harvesting because the frequency of human motion is usually a few hertz whereas the resonance frequency of a piezoelectric cantilever is in the range of tens to hundreds hertz.

The magnetic plucking mechanism used for the Mag-WKEH is illustrated in Fig. 2(a), while the typical displacement profile of the cantilever tip is presented in Fig. 2(b). A primary magnet (PM) is actuated to travel across the secondary magnet (SM) glued at the free tip of a piezoelectric cantilever. As the PM approaches the vicinity of the SM, a repelling force $F_m$ is exerted on the SM. The vertical component of $F_m$, $F_v$ deflects the cantilever from its origin. As the PM continues its path, the cantilever is deflected to a limiting position P1 and then snaps through the PM to the opposite side of the origin, reaching P2. Following that, the cantilever vibrates at its resonance frequency with a decaying amplitude. Therefore, by using the magnetic plucking mechanism, the high-frequency resonant vibration of the piezoelectric bimorph can be excited by the PM in spite of the low frequency of the motion of the PM. As a result, high energy conversion efficiency and high energy output can be achieved. A more detailed exploration of this mechanism can be found in the literature [19].

![Fig. 1](image1.png)

**Fig. 1.** Block diagram of the Mag-WKEH powered WSN: B1–B8 denote the eight piezoelectric bimorphs in the Mag-WKEH; $R_1$ is a 10Ω resistor used to detect the current $I_m$.

![Fig. 2](image2.png)

**Fig. 2.** (a) Illustration of the magnetic plucking action (b) the bimorph tip displacement during magnetic plucking.
2.1.2. Mag-WKEH prototype

The Mag-WKEH prototype used in this study is shown in Fig. 3, which was designed to wear on the leg and to harvest the energy from the knee-joint motions during human walking. The inner hub and the outer ring of the Mag-WKEH are fixed to the shank and the thigh, respectively through two knee braces, while the circuits for power conditioning and wireless sensing sit on the top of the inner hub. During walking, the knee motions actuate the inner hub and the outer ring to rotate relative to each other. As a result, the piezoelectric cantilevers with SMs are plucked by the PMs fixed on the outer ring through the magnetic force.

In the prototype, thirty-two PMs (dimensions: $3 \times 3 \times 3 \text{ mm}^3$; F316-N35, Magnet Expert Ltd., UK) were equally positioned along the inner edge of the outer ring (inner diameter 88 mm). This number of PMs was found to maximise the energy output of the Mag-WKEH, as described elsewhere [19]. Eight piezoelectric bimorphs (T215-H4-303X, dimension $38.1 \times 12.7 \times 0.38 \text{ mm}^3$, Piezo Systems INC, Woburn, US) were fixed in the inner hub with a free length of 26 mm. They are polarised for series operation and each bimorph comprises a 130 μm-thick brass shim sandwiched between two layers of 125 μm-thick PZT. The tip of each bimorph was glued with a secondary magnet (SM) (the same dimensions and supplier with the PMs). The polarisation directions of the magnets were arranged so that the magnetic force between a PM and an SM was always repulsive, as the repulsive force was found to generate a higher energy output than an attractive force. The resonance frequency of the cantilevered bimorph excluding the magnet is 270 Hz. With the added magnet, it is a little lower than this value. The gap between the PM and SM was set to be 1.5 mm. Decreasing the gap can increase the energy output but it also increases the stress level in the bimorph and thus reduces the lifetime. The previous study showed that with a gap of 1.5 mm, the bimorph can operate continuously for 7.3 h without any sign of performance decreasing [19] and thus this gap was selected in this study. The lifetime of the present system is much higher than that of a previous system based on mechanical plucking (~1 h) reported in [11] because the use of the magnets in the present system avoids the direct contact between the input excitation and the piezoelectric bimorphs, which was observed to induce small cracks on the bimorphs in the previous system. The present system weighs 180 g excluding the knee braces and the peak magnetic plucking force $F_p$ is ~0.2 N. Therefore, it imposes little impact on the wearer.

The rectifying circuit consists of eight full-wave rectifiers (BAS70-05/06, Multicomp). Each bimorph was connected to a rectifier individually. The positive and negative output terminals of the eight rectifiers were connected to two common points, respectively, which effectively makes each bimorph-rectifier set in parallel, as schematically shown in Fig. 1 previously.

![Fig. 3. Prototype of the piezoelectric knee-joint energy harvester powered wireless sensing system.](image)

![Fig. 4. A schematic of the power management module (PMM) based on maximum power point tracking (MPPT).](image)

2.2. Power management module (PMM)

It is well-known that the maximum power transfer of a piezoelectric energy harvester occurs when the electric load matches the internal impedance of the energy harvester or in other words, when the voltage across the electric load is half of the rectified open-circuit voltage $V_{OC}$ of the energy harvester [22]. However, the electric load, which is the storage capacitor and the WSN, is usually much smaller than the internal impedance of the energy harvester and is subject to significant variations, leading to a low power transfer efficiency. To address this challenge, a power management module based on maximum power point tracking (MPPT) is developed. Unlike the MPPT circuits reported by other studies [23–25], where power-hungry microcontrollers and/or additional start-up circuits were required, the PMM herein used an analogue differentiator and comparator to realise the MPPT with low-power consumption. A schematic of the PMM is shown in Fig. 4.

A step-down DC-DC converter (LTC3388-3, Linear Technology) was used to converts the high-voltage and low-current outputs of the Mag-WKEH to low-voltage (<3.3 V) and high-current energy to charge the storage capacitor $C_S$. Initially, the DC-DC converter is disabled and can be regarded as open-circuited. The rectified voltage output $V_{in-PMM}$ from the Mag-WKEH charges up the smoothing capacitor $C_s$, and will eventually reach $V_{OC}$ if the DC-DC converter is always disabled, as shown in Fig. 5(a). In such a case, the voltage $V_{in-PMM}$ will increase fast in the beginning, representing high-frequency signals. The increase speed gradually slows down as $V_{in-PMM}$ increases towards $V_{OC}$, representing low-frequency signals. The capacitor $C_{HP}$ and the resistors $R_2$ and $R_3$ in the input terminal of the differentiator form a high pass filter. The high pass filter was designed so that $V_{HP}$ follows the curve shown in Fig. 5(a) and has its maximum value when $V_{in-PMM}$ reaches $V_{OC}$/2. When $V_{HP}$ has its maximum value, its differential $V_{ED}$ is zero. Therefore, the tim-
ing when \( V_{\text{in-PMM}} = V_{\text{DC}}/2 \) can be determined by \( V_{\text{ED}} = 0 \). When the DC-DC converter is controlled by the MPPT to turn on/off, an illustration of the waveforms of \( V_{\text{in-PMM}}, V_{\text{IP}} \) and \( V_{\text{ED}} \) is presented in Fig. 5(b), which was obtained by simulation in SPICE. \( V_{\text{ED}} \) is compared with a pre-set reference signal, \( V_{\text{ref}} \) by a comparator. When \( V_{\text{ED}} \) is zero, i.e. \( V_{\text{in-PMM}} = V_{\text{DC}}/2 \), the comparator sends out a signal pulse \( V_{\text{comp}} \) to enable the DC-DC converter. As a result, energy generated by the Mag-WKEH is transferred at its maximum power point to \( C_{\text{S}} \). Because of the energy transfer, \( V_{\text{in-PMM}} \) decreases and is lower than \( V_{\text{DC}}/2 \). Consequently, \( V_{\text{IP}} \) decreases from the maximum value, leading to a negative \( V_{\text{ED}} \), and the DC-DC converter is disabled. \( C_{\text{S}} \) will be charged up again by the Mag-WKEH until \( V_{\text{in-PMM}} \) reaches \( V_{\text{DC}}/2 \). The energy transfer process will start again and the cycles are repeated. With the PMM, the energy transfer from the Mag-WKEH to the electric load always occurs at \( V_{\text{DC}}/2 \), and therefore, high energy transfer efficiency is achieved.

The differentiator and comparator in the circuit are powered by the Mag-WKEH through the internal rail of the DC-DC converter. The internal rail operates even when the DC-DC converter is disabled. The voltage provided by the internal rail is equal to \( V_{\text{in-PMM}} \) initially when \( V_{\text{in-PMM}} \) is lower than 4.6 V but will become steady at 4.6 V when \( V_{\text{in-PMM}} \) is higher than 4.6 V. To obtain a relatively stable power supply to the differentiator and comparator, a capacitor \( C_{\text{C}} \) and a diode \( D_{1} \) are used. \( C_{\text{C}} \) is used to hold the voltage supply while \( D_{1} \) is used to prevent the energy stored in \( C_{\text{C}} \) from flowing back to the DC-DC converter when \( V_{\text{in-PMM}} \) momentarily drops below 4.6 V. The power consumption of the MPPT (the differentiator and the comparator) used in this study is around 3.2 μW [26], which is 100 times less than the MPPT circuit using a microcontroller [25] and 16 times less than the MPPT circuit using a combination of analogue circuits and FPGA [24].

### 2.3. Energy-aware interface (EAI)

An energy-aware interface was introduced to manage the energy flow from the storage capacitor \( C_{\text{S}} \) to the WSN to ensure that enough energy is accumulated for the WSN to perform the requested tasks in its active phase and that the WSN does not consume energy in its non-active phase. The EAI uses a voltage supervisor (LTC2935-1, Linear Technology, United States) to monitor the voltage \( V_{\text{CS}} \) of the storage capacitor and to control the on/off of a MOSFET switch, as shown in Fig. 6(a). The typical trend of \( V_{\text{CS}} \) under the supervision of the EAI is illustrated in Fig. 6(b).

Initially, the storage capacitor \( C_{\text{S}} \) is charged up and the WSN is at its non-active phase. When \( V_{\text{CS}} \) increases to a pre-set threshold \( V_{\text{on}} \) (3.15 V in this case), the voltage supervisor turns on the switch (MOSFET switch 1 unless specified), and the energy stored in \( C_{\text{S}} \) is discharged to the WSN, enabling the WSN to switch from a non-active phase to an active phase for sensing and transmitting data. During the active phase, the WSN monitors \( V_{\text{CS}} \). When \( V_{\text{CS}} \) is lower than \( V_{0} \) (determined by the WSN and described in Section 2.4), the WSN transmits all the sampled data and then resets the voltage supervisor to turn off the switch at \( V_{\text{CS}} = V_{\text{off}} < V_{0} \). As a result, the WSN is disconnected with \( C_{\text{S}} \) and is turned to the non-active phase while the capacitor can charge up again if there is input energy from the Mag-WKEH. The system will remain in the non-active phase until \( V_{\text{CS}} \) reaches \( V_{1} \) again, and then the cycles repeat. By using the EAI, the voltage supplied to the WSN is regulated to being between \( V_{\text{off}} \) and \( V_{\text{on}} \).

### 2.4. Wireless sensor node (WSN)

A schematic of the hardware of the WSN is shown in Fig. 7. Three sensors were deployed to collect information from the surroundings. They are an ADXL335 3-axis accelerometer (Analog Devices International, Limerick, Ireland, UK), an MCP9700 temperature sensor (Microchip Technology, Inc., Chandler – Arizona, USA), and a humidity sensor (HII-5030, Honeywell, USA). A microcontroller unit (MCU) (JN5148, NXP Semiconductors, Cheshire – Manchester, UK) was utilised to coordinate the data sensing and transmission. It complies with 2.4 GHz IEEE 802.15.4 standard and has added features such as a 128 kb random access memory (RAM) and a 4 Mbit
serial flash memory. The MCU has four analogue-to-digital converters (ADCs). ADC1 is shared by the temperature sensor and the humidity sensor. The MCU selects one of the two sensors by controlling the on/off of MOSFET switch 2 and 3. The other three ADCs are individually terminated to the three outputs (acceleration in x-, y- and z-axis) of the 3-axis accelerometer. The base station (not shown in Fig. 7), which has the ability to collect, store, and process data transmitted by the WSN, was placed at a distance of 4 m.

The WSN including all the sensors can work in a wide voltage range. However, to interpret the signals measured by the sensors, the voltage supplied to the sensors when the measurement is taken, i.e. the reference voltage needs to be known. The reference voltages for the temperature and humidity sensors are measured by the MCU when the two sensors take readings. For the accelerometer, a voltage reference (ISL21080CH325, Intersil, California, USA) was used to provide a fixed reference voltage of 2.5 V.

The operation flowchart of the WSN is shown in Fig. 8. The WSN stays in the non-active phase until the EAI turns on the switch. In each active phase, the MCU takes 1 reading from the temperature sensor and the humidity sensor one by one. After that, the MCU takes 3 readings from the 3-axis accelerometer (one reading for each axis) every 10 ms. The readings are stored in the RAM. Each time after a pre-set number of readings (48 readings in this study) have been taken from the accelerometer, the MCU measures $V_{CS}$ to judge whether $V_{CS} \leq V_0$. If not, the MCU will take another 48 readings from the accelerometer and the cycles are repeated. If so, the MCU will turn on the transceiver, transmit all the data in the RAM to the base station and then reset the voltage supervisor in the EAI to turn off the switch so that the WSN is switched to the non-active phase.

It should be noted that the threshold $V_0$ is not a pre-set value to increase the energy efficiency of the system in this study. The energy-aware software has been added to the MCU program to determine the value of $V_0$ based on the energy stored in the $C_{CS}$ and the energy required to transmit all the data packets in the RAM. $V_0$ was the higher value determined by Eqs. (1) and (2)

$$\frac{1}{2} C_{CS} V_0^2 - \frac{1}{2} C_{CS} V_m^2 = (n + 1) E_x + E_{\text{sample}}$$ \hspace{1cm} (1)

$$\frac{1}{2} C_{CS} V_0^2 - \frac{1}{2} C_{CS} V_x^2 = E_{\text{sample}}$$ \hspace{1cm} (2)

where $V_m$ is the minimum voltage required to operate the WSN (2.4 V); $n$ is the number of transmissions required to transmit all the data stored in the RAM to the base station; $E_x$ is the energy required to make one transmission comprising 48 readings; $E_{\text{sample}}$ is the energy required to sample 48 readings from the accelerometer. $V_x$ is the reference voltage of the accelerometer (2.5 V). Eq. (1) ensures that the energy stored in the $C_{CS}$ can be fully exploited to achieve the maximum active time while all measured data can be safely transmitted before the voltage of the storage capacitor becomes too low to operate the WSN. Eq. (2) makes sure that a fixed voltage reference of 2.5 V is always available when the WSN is on. The value of the $V_0$ can also be pre-set by programming the MCU if needed. By changing $V_0$, the active time and the warm start time can be manipulated to suit different application requirements. For instance, both the active time and warm start time can be reduced by increasing $V_0$ if the application requires an active phase at an increased rate but a reduced time period.

It is worthwhile mentioning that the three sensors deployed were carefully calibrated and the data transmission of the WSN was validated by comparing the data received in the base station with the data directly measured at the sensors. The WSN was designed for general purposes. With the three sensors deployed, it can be used in various applications where sensing of vibration, temperature or humidity is required. When the WSN is placed in proper positions on the human body, the acceleration measurement can be used for a range of health monitoring applications such as classifying activities of daily living [27], step counting [28] and fall detection [29].

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**Fig. 7.** A schematic of the hardware of the wireless sensor node.

**Fig. 8.** A flowchart of the operation cycles of the WSN.
3. Characterisation methods

The experimental tests were performed to characterise the power generation of the Mag-WKEH and the performance of the whole system. In the tests, a human subject wearing the system walked on a treadmill to generate energy to power the WSN, as shown in Fig. 9. A base station was placed at a distance of 4 m to communicate with the WSN. The base station was connected to a laptop, which was used to monitor the data received by the base station.

In each test, the wearer walked continuously for 3 min at a constant speed ranging from 3 to 7 km/h. Before each test, the energy stored in $C_{SS}$ was fully discharged by connecting it with a resistor. When the Mag-WKEH was actuated by the knee-joint motions to produce energy, the voltage across the input terminal of the PMM, $V_{in-PMM}$ and the voltage across the current detecting resistor $R_1$, $V_1$ were measured by an NI 9229 analogue input module installed on cDAQ-9147 chassis (National Instrument Newbury, UK). The voltage $V_{CS}$ and current $I_{CS}$ in the storage capacitor were measured by a system source meter (2612B, Keithley Instruments Inc., Ohio, United States), while the voltage $V_W$ and current $I_W$ in the WSN were recorded by another 2612B system source meter. The data recording of the NI 9229 module and the 2612B source meters was synchronised by a LabVIEW program running on the PC, which also displayed the measured results in real time. The test at each walking speed was repeated five times and the average results with the standard deviation are presented.

With the voltage and currents recorded, the energy distribution in the system can be calculated by using the following equations. The energy generated by the Mag-WKEH $E_g$ is

$$E_g(t_f) = E_{loss-rect}(t_f) + E_{in-PMM}(t_f)$$  \hspace{1cm} (3)$$

where $E_{loss-rect}$ is the energy loss in the rectifiers and $E_{in-PMM}$ is the energy input to the PMM. With the voltage drop across each Schottky rectifier estimated to be 0.6 V, $E_{loss-rect}$ is calculated as

$$E_{loss-rect}(t_f) = 0.6 \sum_{k=1}^{j} \frac{V_1(t_k)}{R_1} \Delta t$$  \hspace{1cm} (4)$$

where $\Delta t$ is the sampling period. The energy input to the PMM $E_{in-PMM}$ is

$$E_{in-PMM}(t_f) = \sum_{k=1}^{j} V_{in-PMM}(t_k) \frac{V_1(t_k)}{R_1} \Delta t$$  \hspace{1cm} (5)$$

The energy stored in the storage capacitor $E_{CS}$ is

$$E_{CS}(t_f) = \sum_{k=1}^{j} P_{CS}(t_k) \Delta t = \sum_{k=1}^{j} V_{CS}(t_k) I_{CS}(t_k) \Delta t$$  \hspace{1cm} (6)$$

where $P_{CS}$ is the instantaneous power in the capacitor.

The energy consumed by the WSN is

$$E_W(t_f) = \sum_{k=1}^{j} P_W(t_k) \Delta t = \sum_{k=1}^{j} V_W(t_k) I_W(t_k) \Delta t$$  \hspace{1cm} (7)$$

where $P_W$ is the instantaneous power consumed by the WSN.

Duty cycle is used to assess the ability of Mag-WKEH powering the WSN, and is defined as

$$Duty\ cycle = \frac{t_a}{t_a + t_w} \times 100\%$$  \hspace{1cm} (8)$$

where $t_a$ and $t_w$ are the active time and warm start time, respectively, as illustrated in Fig. 6(b).

4. Characterisation results and discussions

The experiment was first performed at a walking speed of 4 km/h, which is a comfortable walking speed determined by the wearer to carry out the test. Fig. 10 shows time profiles of the energies generated and consumed in the system at this walking speed. In 180 s, the Mag-WKEH generated an energy output $E_g$ of 490 mJ, corresponding to an average power of 2.72 mW. This means that on average, each bimorph generated 0.34 mW at 4 km/h. The individual output of each bimorph was not measured in this study because of the difficulty in connecting wires from the rotating bimorphs, but can be found in the previous study [19]. Of the energy generated by the Mag-WKEH, 95.9% was extracted by the PMM ($E_{in-PMM} = 470 \text{ mJ}$), while 4.1% was dissipated in the rectifiers ($E_{loss-rect} = 20 \text{ mJ}$). The capacitor stored energy $E_{CS}$ of 125.5 mJ and the WSN consumed energy $E_W$ of 255 mJ. The energy output from the PMM, which is the sum of $E_{CS}$ and $E_W$, is 380.5 mJ, corresponding to an average power of 2.11 mW. Here the energy loss in
the EAI is ignored, because the measured current through the EAI is negligible (∼0.95 μA during the non-active phase and ∼10 μA during the active phase) compared with $I_{CS}$ and $I_W$, which are in milliamp range.

The maximum power output of the Mag-WKEH measured at 4 km/h is 3.4 mW, which was obtained by connecting the Mag-WKEH with an optimal load resistor of 15 kΩ after the rectifying circuit. This means that even with the varying impedance of the succeeding circuits, the Mag-WKEH achieved 80% of its maximum power output. This efficiency is about 2–4 times of those (19–43%) reported in [30], where a commercial power conditioning board was used in a vibration energy harvester powered strain gauge. It is also much higher than the efficiency of 51% reported in [11], where the rectified energy was used to charge a storage capacitor directly in a wearable energy harvester powered WSN. The high power generation of the present system is because the PMM has improved the power transfer efficiency of the energy harvester through the maximum power point tracking. The conversion efficiency of the PMM can be evaluated by the ratio of the power output (2.11 mW) and input (2.61 mW) to the PMM and is 81.0%, opposed to the efficiency of 65%–76% reported in literature [25] and 80% reported in literature [31], which both employed MPPT to improve the power output of piezoelectric energy harvesters.

At 4 km/h, after charging the storage capacitor for 62.21 s (cold start time $t_C$), the Mag-WKEH is able to power the WSN for a period of 1.99 s (active period $t_a$) every 20.2 s (warm start time $t_w$), as can be observed in Fig. 11, and the duty cycle is 8.97%, as calculated by Eq. (8). The detailed working process of the system is discussed below.

From the beginning to 62.21 s, the storage capacitor $C_{CS}$ was charged up by the Mag-WKEH, and its voltage $V_{CS}$ increased steadily from zero to 3.15 V, as shown in Fig. 11(a). $E_{CS}$ (Fig. 11(d)) increased steadily and reached 120 mJ at 62.21 s. During this period, the EAI turned off the switch; as a result, there was no energy flowing from $C_{CS}$ to the WSN, which was at its non-active phase.

As soon as $V_{CS}$ reached 3.15 V, the EAI turned on the switch, $C_{CS}$ discharged its energy to the WSN. As a result, a drop in $V_{CS}$ and $E_{CS}$ was observed. Both negative and positive values were observed in $I_{CS}$ within this period. Negative $I_{CS}$ suggests the storage capacitor being discharged, whereas positive $I_{CS}$ suggests the capacitor being charged up. The charging-up of the capacitor is because the instantaneous current output from the PMM ($I_{out-PMM}$) denoted in Fig. 1 was larger than the current $I_W$ needed by the WSN. Therefore, only part of $I_{out-PMM}$ flew to the WSN directly to power the latter; whistle the rest flew to the storage capacitor, charging up the capacitor and leading to the increase in both $V_{CS}$ and $E_{CS}$. Because the positive values of $I_{CS}$ only lasted for very short periods, the increases in $V_{CS}$ and $E_{CS}$ are too subtle to observe in Fig. 11(a) and (d) in the current scale. The discharging of $C_{CS}$ lasted for 1.99 s until the switch was turned off. During this period, $C_{CS}$ released energy of 37.41 mJ, corresponding to an average power of 18.80 mW.

During the period when the switch was on, a voltage and current appeared in the WSN, and the WSN was switched into its active phase. In a period of 1.99 s, the WSN in total sampled 482 readings (1 reading from the temperature sensor, 1 reading from the humidity sensor and 160 × 3 readings from the accelerometer) from the three sensors, and made 10 transmissions to transmit all the data to the base station. The base station successfully received all the data. The WSN consumed energy of 40.81 mJ, corresponding to an average power of 20.5 mW. This energy is higher than the energy discharged by the $C_{CS}$ (37.41 mJ)-the difference in energy, 3.4 mJ was supplied by the Mag-WKEH.

The WSN started the data transmission when $V_{CS} = 2.55$ V, and finished the all data transmission when $V_{CS} = 2.49$ V, which is just above the minimum voltage (2.4 V) required to operate the WSN. This suggests that the energy stored in the capacitor was fully exploited by the WSN to achieve the maximum active time while the measured data were successfully transmitted. This is attributed to the new energy-aware software feature introduced in the MCU program, as discussed in Section 2.4. Following finishing the data transmission, the MCU reset the EAI so that the switch in the EAI was turned off and the voltage supply to the WSN was shut down. Consequently, the WSN was turned to the non-active phase and did not consume energy from the Mag-WKEH or the storage capacitor in this period. A gradually decreasing voltage was observed across the WSN, which resulted from the discharging of the decoupling
5. Conclusions

This paper reported the whole system integration of the Mag-WKEH with the energy-aware WSN through the PMM and the EAI to establish an energy harvesting powered wireless sensing system with increased energy efficiency and increased data transmission capability. The capability of the Mag-WKEH to power the WSN was experimentally studied. The energy generated by the Mag-WKEH and the energy distribution of the system were characterised.

The Mag-WKEH employed repulsive magnetic forces to provide frequency up-conversion from the low frequency of human walking to the resonance of the Mag-WKEH. As the walking speed increased from 3 to 7 km/h, the power generation increased from $1.9 \pm 0.12$ to $4.5 \pm 0.35$ mW, which corresponds to 80% of the maximum power output of the Mag-WKEH when terminated with an optimal load resistor. This high efficiency is attributed to the use of the PMM. The harvested energy was successfully used to power the WSN for an active time of $2.0 \pm 0.1$ s with a warm start time between $29.49 \pm 1.7$ and $14.05 \pm 0.65$ s. In each active time, the WSN sensed 480 readings from the sensors and transmitted all the data to the base station. With the long active time and the large data transmission capability, the system is particularly suitable for dynamic signal monitoring. Future work will develop an ergonomic prototype of the Mag-WKEH powered wireless sensing system and deploy proper sensors in the WSN for body condition monitoring.

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References

[1] S. Patel, H. Park, P. Bonato, L. Chan, M. Rodgers, A review of wearable sensors and systems with application in rehabilitation, J. Neuroeng. Rehabil. 9 (2012) 1.
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