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Energy harvesting during human walking to power a wireless sensor node

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ABSTRACT

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 $6.6 \pm 0.36\%$ to $13 \pm 0.5\%$ 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.

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 those 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-

Abbreviations: Mag-WKEH, magnetically plucked wearable knee-joint energy harvester; PMM, power management module; MPPT, maximum power point tracking; EAI, energy-aware interface; WSN, wireless sensor node; PM, primary magnet; SM, secondary magnet; MCU, microcontroller unit.

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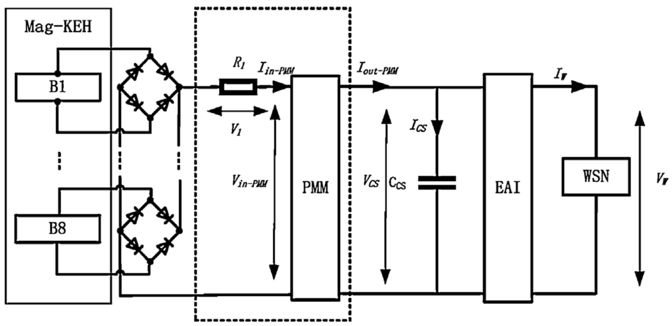

Fig. 1. Block diagram of the Mag-WKEH powered WSN: B_1–B_8 denote the eight piezoelectric bimorphs in the Mag-WKEH; R_1 is a 10 Ω resistor used to detect the current I_{in-PMM}.

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 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 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 (B_1–B_8), 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_{CS}) 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 out. 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].

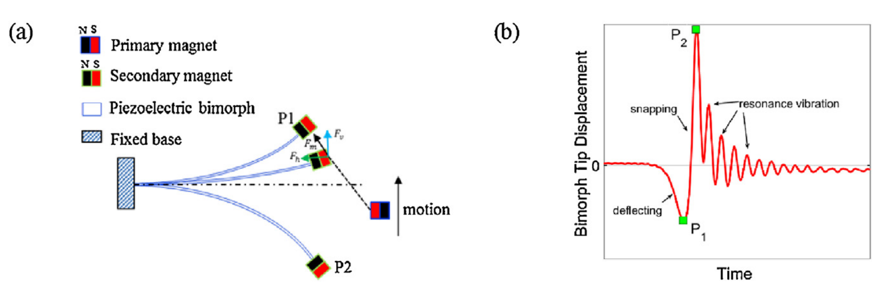

Fig. 2. (a) Illustration of the magnetic plucking action (b) the bimorph tip displacement during magnetic plucking.