

Research Article

A Preliminary Study on the IoT-Based Pavement Monitoring Platform Based on the Piezoelectric-Cantilever-Beam Powered Sensor

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Green and sustainable power supply for sensors in pavement monitoring system has attracted attentions of civil engineers recently. In this paper, the piezoelectric energy harvesting technology is used to provide the power for the acceleration sensor and Radio Frequency (RF) communication. The developed piezoelectric bimorph cantilever beam is used for collecting the vibrational energy. The energy collection circuit is used to charge the battery, where the power can achieve 1.68 mW and can meet the power need of acceleration sensor for data collection and transmission in one operation cycle, that is, 32.8 seconds. Based on the piezoelectric-cantilever-beam powered sensor, the preliminary study on the IoT-based pavement monitoring platform is suggested, which provides a new applicable approach for civil infrastructure health monitoring.

1. Introduction

With the development of IoT (Internet of Things) technology, the demand for sensor in the engineering industry is increasing dramatically; in the meantime the power supply for the sensor in the process has attracted more and more attention of researchers. Bogue (2009) considered that the power supply has been a great problem for the large-scale engineering application of sensors [1]. To solve this problem, there have been various new energy approaches. Considering the structural characteristics of pavements, one of the most effective energy harvesting techniques is to use the piezoelectric material as one component of the pavement materials, where the piezoelectric effect will collect the vibration mechanical energy on the roads and convert it into electrical energy to supply power. The piezoelectric power supply device has the advantages of small volume and can be used for long-term operation without device replacement.

Priya (2005) developed a pocket-sized windmill to provide power for wireless networks [2]. Ammar et al. (2005) studied the necessary parts of self-powered sensor nodes [3]. Yuse et al. (2008) [4] and Guyomar et al. (2007) [5] used the classic energy recovery circuit to design a self-powered health monitoring system. Muralt et al. (2009) designed and manufactured the film piezoelectric cantilever [6]. Lee et al. (2009) manufactured 3-1 and 3-3 type cantilever piezoelectric power generator using MEMS techniques [7]. Hu et al. (2012) developed a nanopower generator based on ZnO nanowire arrays. The power density of the devices was 0.2 W/cm^3 [8]. Shi et al. (2014) designed a self-powered system using the low temperature thermoelectric material bismuth telluride (Bi_2Te_3) [9]. Sang et al. (2015) analyzed structure and theoretical model of the self-powered sensor system [10]. Aung et al. (2014) combined with the application of wireless communication and energy harvesting thermoelectric generator (TEG) to study the effectiveness of new

high temperature electrochemical sensors [11]. Cho et al. (2016) designed a piezoelectric energy acquisition system with magnetic oscillations that harvested inertial energy and vibrational energy [12]. Yeo et al. (2016) studied the PCM energy collector of the double crystal Pb (Zr, Ti)O-3 (PZT) film on the Ni foil deposited by rf magnetron sputtering [13]. Hsu et al. suggested a locally amplified strain sensor based on the piezoelectric polymer [14]. Acer et al. (2015) developed a distributed piezoelectric sensor for contact detection [15]. Deligianni et al. (2016) conducted researches on the piezoelectric thick-film sensors for embedding in joints [16].

Although there has been some progress in the self-powered sensor area, the current research has two limitations: first, the self-power concept has only been implemented in some of the systems but has not been comprehensively applied in the design of sensors; second, the self-power capability is not implemented in the pavement monitoring system. Although there have been many researches on the pavement performance analysis [17–22] and pavement materials areas [23, 24], there is still a lack of researches on the real-time monitoring of pavement structures. To overcome these limitations and further develop the self-powered sensor technique, in this study, the bimorph piezoelectric-cantilever-beam type pressure transducer was used for collecting environment vibration energy. Based on the piezoelectric self-powered sensor, the preliminary study on the IoT-based pavement monitoring platform is suggested and designed, which provides a new applicable approach for civil infrastructure health monitoring.

2. Design of Self-Powered Wireless Sensor

In this study, the self-powered wireless acceleration sensor is developed, which is mainly used for vibration monitoring of small and medium sized bridge. When the vehicle travels on the bridge, the vehicle and the bridge constitute the vibration system. The bridge vibration state is relevant to the bridge structure, the vehicle dynamic characteristics, the vehicle speed, and the vehicle flow.

The designed self-powered sensor mainly includes the following parts: piezoelectric vibration unit, piezoelectric energy collection circuit, energy storage unit, output control circuit, data acquisition/processing unit, sensor unit, and wireless communication unit. Figure 1 shows the structure design of the piezoelectric accelerometer.

The piezoelectric vibration energy collecting unit uses bimorph piezoelectric-cantilever-beam type transducer. The natural frequencies of the piezoelectric cantilever are closer to the external vibration frequency, and more electricity can be generated.

The designed power management chip is used to manage the battery and the external power supply. LTC3331 microenergy collection chip from Linear Technology Company is used. In order to provide the 3.0 V voltage for the motherboard, the chip is used for low voltage conversion, to provide the required operating voltage of the system. The energy collection circuit is charged by using bimorph

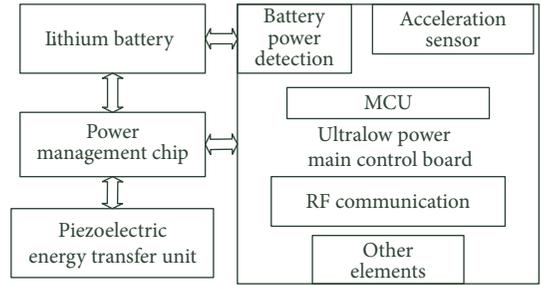


FIGURE 1: Structure design of piezoelectric self-powered acceleration sensor.

TABLE 1: Energy collection effect under different input clamp voltage.

Number	Input voltage high potential (V)	Input voltage low potential (V)	Output energy (J)	Average power (mW)
1	6	5	0.114	1.143
2	8	5	0.128	1.279
3	10	5	0.144	1.435
4	12	5	0.154	1.538
5	14	5	0.160	1.596
6	16	5	0.169	1.686

pressure piezoelectric cantilever. The energy collection efficiency can be improved by selecting different switch circuit voltage clamp. Figure 2 shows the energy collection circuit and the output circuit board. Table 1 shows the energy collection effect of different input clamp voltage. Note that for input voltage high potential at 16 V and low potential at 5 V, the collected energy in the circuit is up to 1.68 mW.

The piezoelectric cantilever beam is excited by an external excitation generated by an exciter to the fixed end of the cantilever beam, where the displacement amplitude is 0.5 m, the frequency is 10.6 Hz which is also the resonant frequency of the piezoelectric cantilever beam, and the displacement of the free end is 10 mm. As shown in Figure 3, the output current from the piezoelectric cantilever and input into the LTC 3331 energy collection circuit are rectified. A 2000 ohm resistor in V_{in} section is connected to measure the input current based on different voltages, and an oscilloscope is used to measure the voltage at A point and B point. The turn-on voltages are set to 6 V, 8 V, 10 V, 12 V, 14 V, and 16 V, respectively. Figure 4 shows the relationship between the displacement and the open circuit voltage.

The cut-off voltage of the energy collection circuit is 5 V. There are a total of 1250000 sampling points at 100 s in the oscilloscope. Using the integration operation by MATLAB, the energy of the input energy collection circuit in 100 s is obtained, as shown in Table 1. It is observed that the higher the potential, the higher the output energy.

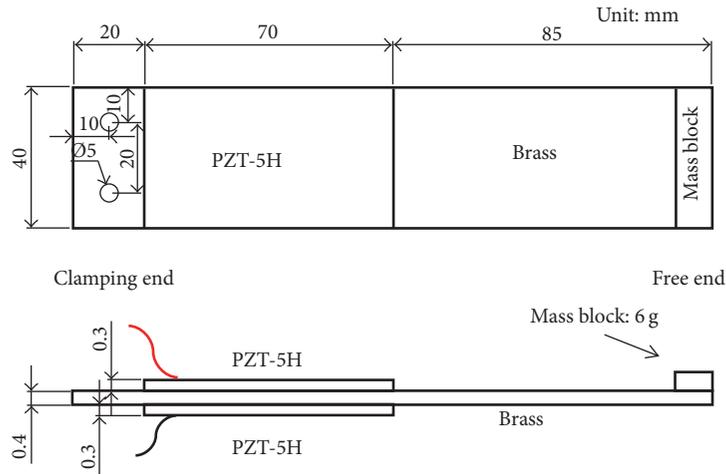


FIGURE 2: Design of bimorph piezoelectric cantilever beam.

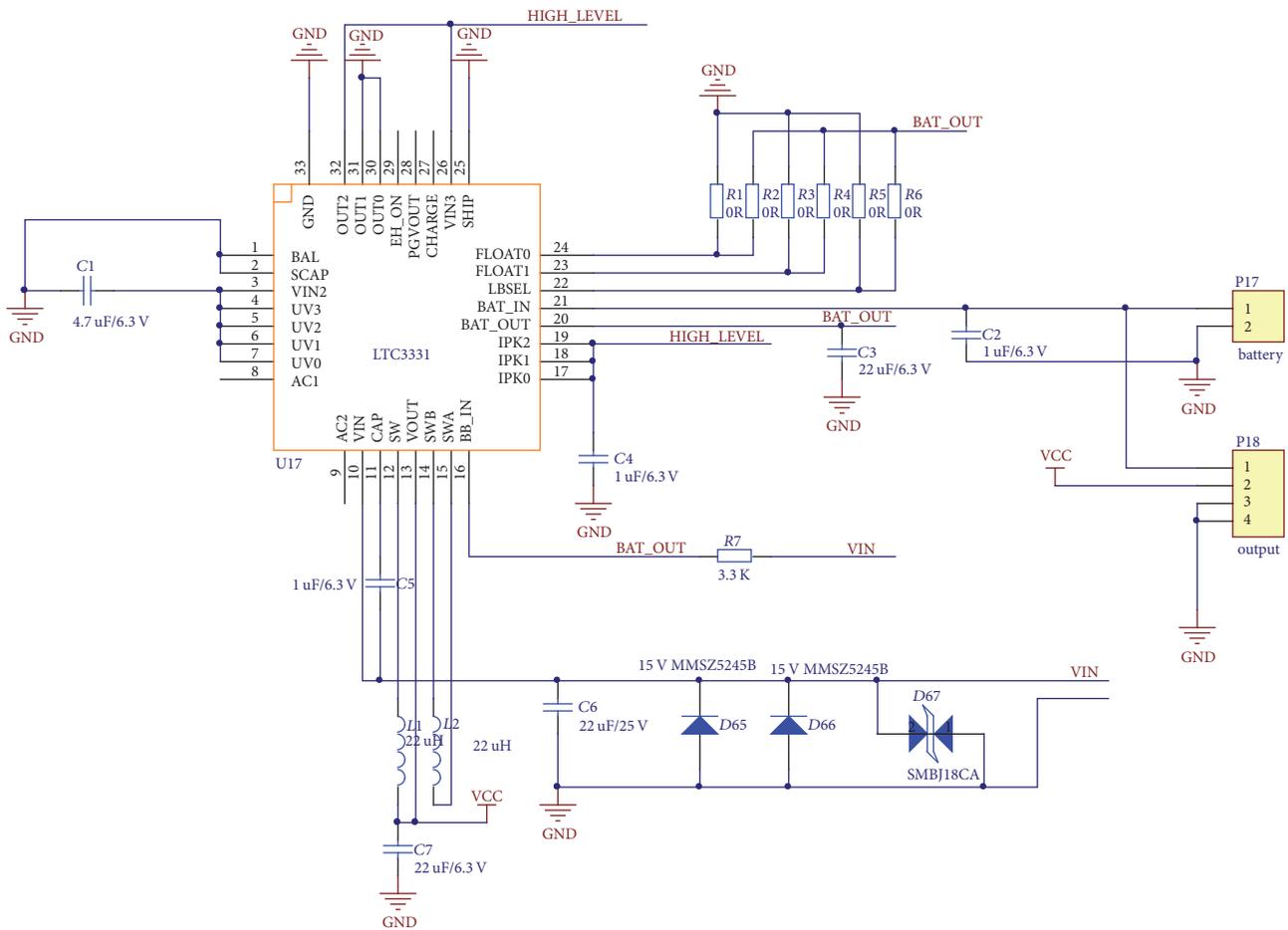


FIGURE 3: Design of piezoelectric energy harvesting circuit.

3. Power Consumption Analysis of the Self-Powered Piezoelectric Sensor

As shown in Figure 5, a complete working cycle of the self-powered piezoelectric sensor is divided into four stages: sleep, data acquisition, data calculation, and data transmission.

Figure 6 shows the basic work flow of the sensor, where the work steps are divided into the following:

- (1) Measurement starts: using the RTC timing wakeup, the purpose of cycle measurement is achieved. The CPU running speed is set to 2 MHz after wakeup, and the STOP mode is used.

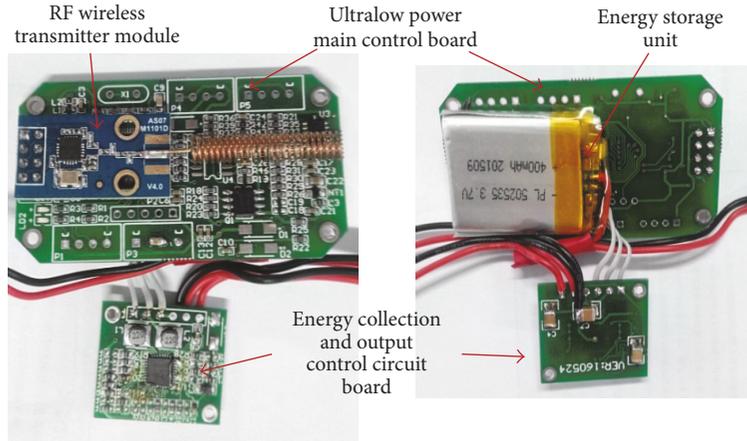


FIGURE 4: Energy collection circuit and battery storage circuit board.

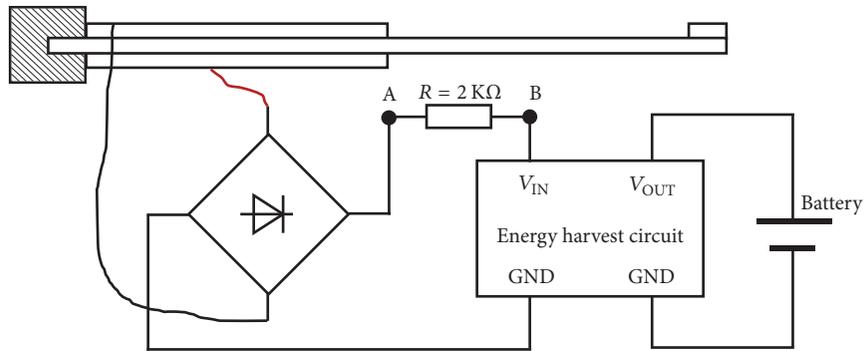


FIGURE 5: Schematic diagram of piezoelectric energy harvesting.

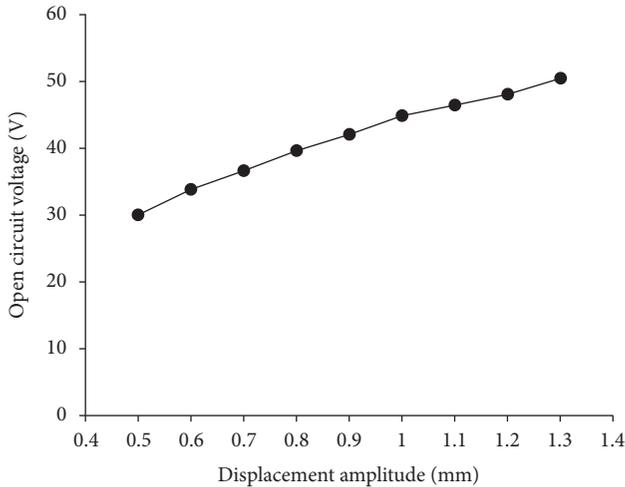


FIGURE 6: Relationship between the displacement and the open circuit voltage.

- (2) After the start of CPU, power is supplied to the acceleration sensor and the time for starting the power is 20 ms.
- (3) When the power supply for the acceleration sensor is ready, the sampling mode is started, and the acceleration

sensor is periodically sampled according to the sampling cycle. The cycle is set as 1/1024 ms and the frequency is 1.024 kHz. To reduce power consumption, CPU uses a regular wakeup, wakeup every 1 ms sampling, after sampling into the STOP mode.

(4) After sampling for 1024 times, the system clock ascends to 32 MHz frequency and conducts FFT transform for the sampled data. The computational time is about 20 ms. After the data processing, the CC1101 emission is started, where emission mode power consumption is about 20 mA and lasts for 20 ms.

(5) After the emission of CC1101, the sensor enters sleep mode.

The power consumption in each working step is shown in Table 2.

The average power consumption of the sensor is adjusted by setting the sleep time of the sensor, and the average power consumption of the sensor can be obtained based on

$$P = \frac{16.635 + 1.23t_s}{t_s + 1.11}, \tag{1}$$

where P is the average power consumption with unit W and t_s is the sleep time of the sensor with unit ms.

It is calculated that the maximum output power of the piezoelectric cantilever is 1.68 mW. It therefore meets the

TABLE 2: Power consumption of each step in a work cycle.

Work step	Operating current/mA	Operating voltage/V	Operating time/ms	Power/mJ
Sleep mode	0.410	3	—	—
Data acquisition	3.84	3	1000	11.52
FFT calculation	4.1	3	50	0.615
Data transmission	25	3	20~60	4.5

power consumption of the sensor. The sleep time is larger than 32.8 s. Considering the energy efficiency, the best time to sleep should be no less than 60 s.

4. IoT-Based Pavement Monitoring Platform

Based on the above designed piezoelectric self-powered sensor, a preliminary IoT-based pavement monitoring platform is suggested and designed. The basic architecture design of IoT-based pavement monitoring platform is divided into three parts: self-powered sensing nodes, gateway nodes, and the cloud platform. The system uses piezoelectricity to supply the power for sensor node. It uses low power communication and low power hardware to reduce the energy consumption of the system and to realize the remote monitoring and control.

The sensing node uses the designed self-powered sensor. The gateway nodes are based on 433 M and GPRS communication and serve as the connection link between sensor networks and the traditional communication network. They connect the sensor networks and the cloud server, improve the data transmission efficiency under the complex environment, and realize the remote control, equipment management, and temperature and humidity monitoring functions. Gateway nodes use RF communication module to communicate with sensor network nodes. To achieve a wide area interconnection, 3G/4G communication module and a carrier network are used. The operators can manage the sensors by using the remote control through the gateway equipment.

The cloud platform includes the cloud server and the web interface. Note our current research is still in the preliminary stage on the piezoelectric-cantilever-beam powered sensor for IoT-based platform. Future studies will be conducted to evaluate the applicability of the self-powered sensor in actual engineering projects.

5. Conclusions

The power supply for sensors in pavement monitoring has always been attracting attentions of civil engineers. For some special service conditions, it is too difficult to provide a safe, stable, and reliable power supply at site environment, which results in the unworkability of the pavement monitoring system. To solve this problem, in this paper, the piezoelectric energy harvesting technology was used to provide power energy for the acceleration sensor and RF communication.

The power of piezoelectric cantilever vibration energy collection system can reach 1.68 mW, which can meet the power need of acceleration sensor for data collection and transmission in one operation cycle, that is, 32.8 seconds. Based on the piezoelectric self-powered sensor, the preliminary study on the IoT-based pavement monitoring platform is suggested, which provides a new applicable approach for civil infrastructure health monitoring.

Conflicts of Interest

The authors declare that there are no conflicts of interest in this paper.

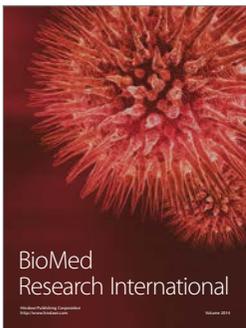
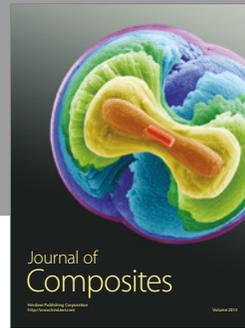
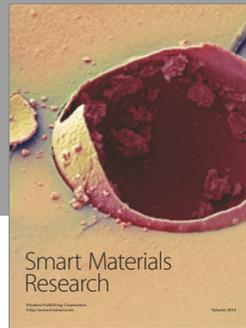
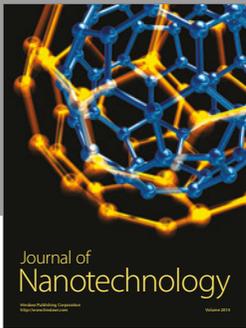
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