

Hybrid Energy Harvester for Medical Sensor Node toward Real-Time Healthcare Monitoring

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Abstract

In healthcare applications, the remote monitoring for moving patients depends on medical sensor nodes, which should be mobile. Thus, the power mains of medical sensor nodes should be disconnected most of the time to monitor natural movements of patients. In this paper, a self-sustainable medical sensor node is proposed for healthcare monitoring applications. The node implementation consists of a microcontroller unit (MCU), a photo-plethysmography (PPG) sensor, a Bluetooth low energy (BLE) module, and a MPU module that includes a gyroscope with accelerometer. The power supply of the node is a hybrid energy harvester developed to provide a sustainable energy for the sensor node. The harvester is composed of a photovoltaic (PV) panel, a thermoelectric generator (TEG) module, a DC-DC converter, and a super-capacitor. Experimental results illustrate that the proposed node can monitor a physiological data on a mobile device using the BLE Terminal application.

Keywords: medical sensor node, healthcare, energy harvesting, super-capacitor

1. Introduction

In the last decade, sensor nodes have played an effective role in biomedical fields [1-3]. However, the power supply of sensor nodes is frequently batteries, which have limited lifetime [4-5]. Energy harvesters can extend the battery lifetime of sensor nodes [6-9]. Photovoltaic and thermoelectric energy harvesters are used for the reason that they have high power density [10]. Thus, a hybrid photovoltaic-thermoelectric energy harvester is implemented to overcome the limitation of using batteries.

There are multiple sensor nodes presented for medical applications [11-13]. Toh et al. [11] present an autonomous wearable sensor node with flexible photovoltaic energy harvesting. It utilizes an analog maximum power point tracking technique to manage the power of the node. Lim et al. [12] introduce a solar energy harvester for a sensor device. It includes a photovoltaic panel (PV), a DC-DC boost converter, and a battery. Tran and Chung [13] present an autonomous sensor node, which consists of a Photoplethysmogram (PPG) sensor and an Electrocardiogram (ECG) sensor, to monitor a patient's physiological data supplied by battery. The data of the sensor node is visualized by using the myMonitor Android application.

This paper presents an autonomous medical sensor node powered by a sustainable hybrid energy harvester. This harvester is developed based on a low-power DC-DC converter with two super-capacitors. These super-capacitors are used as backup power supply with overall capacity of 12.5 F. The harvested hybrid energy is sufficient to supply the medical sensor node. The data of the sensor node is collected by PPG, gyroscope and accelerometer sensors. The data is transmitted to the BLE Terminal android application via BLE technology.

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The reminder of the paper is organized as follows: Section 2 introduces the energy harvesting technology. Section 3 presents the development of the medical sensor node with the hybrid energy harvester. The experimental results are illustrated in section 4. Section 5 presents the conclusion of the paper.

2. Energy Harvesting Technology

Energy harvesting is a technology that converts and stores an energy from an environmental source for supplying autonomous devices [14]. The generic block diagram of energy harvesting technology is illustrated in Fig. 1. The block diagram consists of five blocks. The first one is environmental source, i.e. light, thermal, radio frequency (RF), vibration, wind, etc. Energy harvester is the second block, which converts an environmental energy into electrical energy. The third block refers to conversion and energy management, which is used to maximize the output power of the energy harvester. The fourth block is energy storage, which stores the harvested energy as backup. Energy storage can be rechargeable batteries or super-capacitors. There is a trade-off between them in terms of energy density and charging cycles. Super-capacitors have unlimited charging cycles in comparison with batteries, while the batteries have higher energy density than super-capacitors [15]. Finally, energy harvesting technology is employed to power a device, e.g. a medical sensor node.

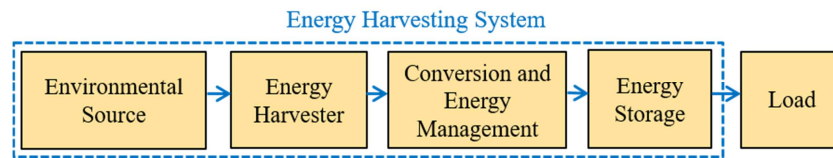


Fig. 1 The generic block diagram of energy harvesting technology

Table 1 shows power densities of different energy sources [16]. An outdoor light has a power density of 15 mW/cm^2 , while the power density of an indoor light is $100 \text{ } \mu\text{W/cm}^2$. Also, the power density from a thermal energy source is $60 \text{ } \mu\text{W/cm}^2$, and the power density from a vibration energy source is $335 \text{ } \mu\text{W/cm}^2$. In addition, the radio frequency (RF) can generate a power in the range of 0.1 to $1 \text{ } \mu\text{W/cm}^2$. Finally, an air flow energy source has a power density of $7600 \text{ } \mu\text{W/cm}^2$ at a velocity of 5 m/s . It is clear that the highest energy source is outdoor light. On the other hand, the thermal energy provides a convenient energy source with medical sensor nodes due to the fact that body heat is an inherent characteristic of human body. Therefore, the combination of light and thermal energy sources is used in the proposed system.

Table 1 Power densities of different energy sources

Energy Source	Power Density ($\mu\text{W/cm}^2$)
Light (outdoors)	15000
Light (indoors)	100
Thermal	60
Vibration	335
Radio frequency (RF)	0.1–1
Air flow	7600 (at 5 m/s)

3. Development of Medical Sensor Node with Hybrid Energy Harvester

3.1. Architecture

Fig. 2 demonstrates the proposed architecture of the medical sensor node with hybrid energy harvester. This architecture is composed of a PPG sensor to measure the heartbeats of a patient, a MPU module that include an accelerometer to sense the patient's linear accelerations and a gyroscope to detect the angular velocity, a BLE module that send the sensors data to a smartphone, and a microcontroller unit (MCU) that collect these sensors data for processing. This sensor node is powered by a hybrid energy harvester, which contains a thermoelectric generator (TEG) module to generate an electric power of the thermal energy of patient body, a PV panel to convert the light into an electric power, and a DC-DC converter to fix the voltage of PV panel and TEG module to charge a small-size super-capacitor.

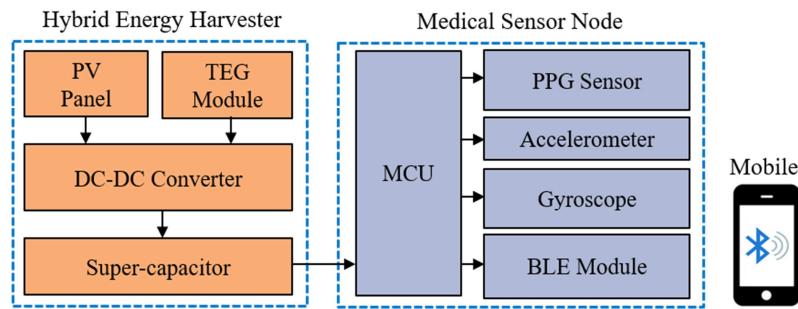


Fig. 2 The architecture of the medical sensor node with the hybrid energy harvester

3.2. Hardware and software implementation

The hardware implementation of the medical sensor node with hybrid energy harvester is shown in Fig. 3. It includes a flexible PV panel (MPT3.6-75) with an area of $7.2 \times 6.0 \text{ cm}^2$ and a TEG module (SP1848-27145). It has a small-size of $4 \text{ cm} \times 4 \text{ cm} \times 0.4 \text{ cm}$. The PV panel and the TEG module are connected in parallel. The DC-DC converter is based on a LTC3105 chip from linear technology[®]. This converter has high efficiency with input voltage from 0.2 to 5 V. The energy storages are two super-capacitors (HV1625-2R7256R) that have capacity of 25 F and voltage rate of 2.7 V. These super-capacitors are connected in series with voltage rate of 5.4 V. The microcontroller unit (MCU) is a low-power AT mega-328p manufactured by Atmel. This unit has speed of 16 MHz with operating voltage of 5 V. The PPG sensor is selected SEN-11574. It is a high range from 0 to 200 bpm. The MPU module is chosen 6050 with accelerometer resolution in the range of -2 to +2 g. Its gyroscope angular velocity is between -250 to +250 degree/second [17]. The used BLE module is BT05 that has the range of 100 meters.

Fig. 4 describes the software flowchart of the medical sensor node. The sensor node is operating in two modes: active and sleep. Firstly, the microcontroller is configured in active mode. Secondly, it continuously measures the data of the sensors. Thirdly, the sensor data are sent for a duration of 3 seconds using the BLE module. Fourthly, the sensors are turned off. Fifthly, the BLE module is slept and then, the microcontroller enters in sleep mode for a period of 597 seconds to save the power consumption of the node. Finally, the previous steps are continuously repeated in a loop [18].

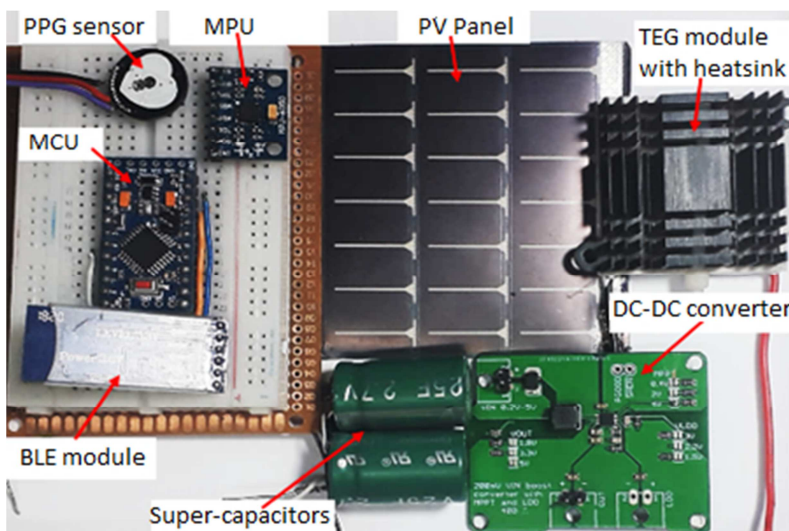


Fig. 3 Hardware implementation of the medical sensor node with the energy harvester

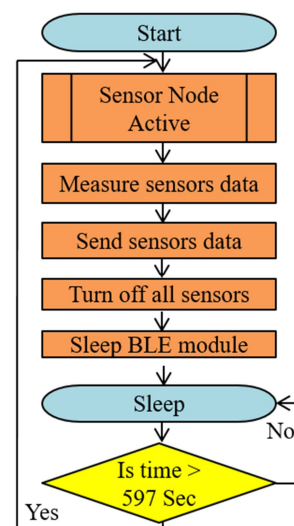


Fig. 4 Software flowchart of the medical sensor node

4. Experimental Results

Fig. 5 describes experimentally the I-V-P electrical characteristics of the PV panel under illumination of 1000 W/m^2 . The orange and blue curves are the photovoltaic power (P_{pv}) and current (I_{pv}) respectively versus the photovoltaic voltage (V_{pv}). The

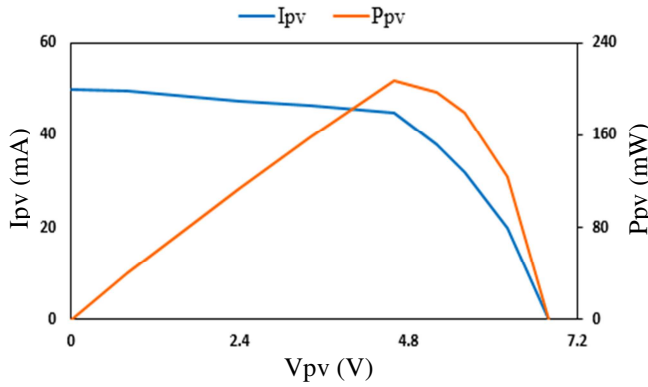


Fig. 5 I-V-P electrical characteristics of the PV panel at 1000 W/m^2

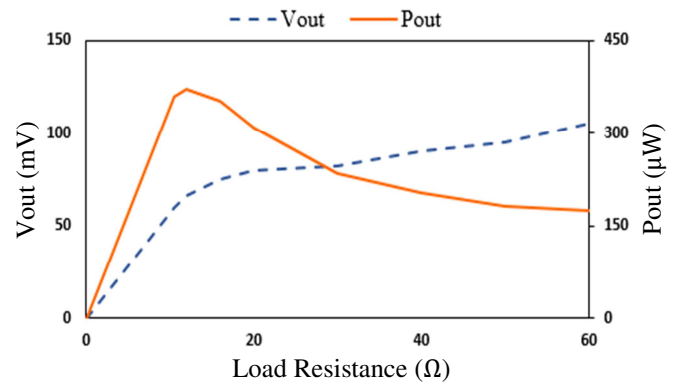


Fig. 6 R-V and R-P characteristic curves of the TEG at $\Delta T = 5 \text{ }^\circ\text{C}$

maximum power reaches to 207 mW at voltage of 4.6V. Fig. 6 shows the R-V and R-P characteristic curves of the TEG module at $\Delta T = 5 \text{ }^\circ\text{C}$. The maximum output power (P_{out}) is measured at 10.5 Ω load resistance. Also, the dashed blue curve shows the maximum output voltage (V_{out}) of 105 mV with a 60 Ω load resistance.

Fig. 7 shows the charging curve of the 12.5 F super-capacitor of the hybrid energy harvester. The voltage of the super-capacitor is increased from 2.6 V to 5 V in 165 minutes. Table 2 demonstrates the charging rate of the 12.5 F super-capacitor. The voltage measurements of the super-capacitor are taken via the EXCEL multi-meter. When the PV panel generates the power higher than the TEG module during the sunlight, the DC-DC boost converter starts to charge the super-capacitor. Under the darkness case, the TEG module supplies power to charge the super-capacitor.

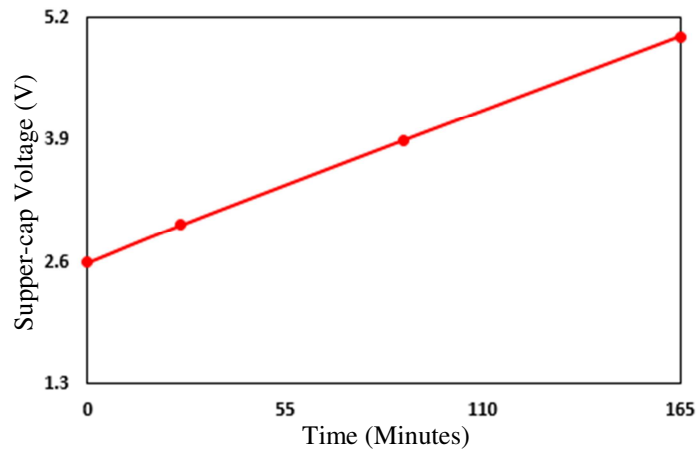


Fig. 7 Charging curve of the 12.5 F super-capacitor

Table 2 Charging rate of the 12.5 F super-capacitor

Time Intervals (min)	Charging Rate (mV/s)	Voltage (V)
0–26	0.25	2.6–3.0
26–88	0.24	3.0–3.9
88–165	0.23	3.9–5.0

Table 3 Power consumption of the sensor node

Mode	Current (mA)	Time (s)	Power (mW)
Active	20	3	100
Sleep	1.5	597	7.5

Table 3 illustrates the measured power consumption of the sensor node for each mode. In active mode, the node consumes current of 50 mA. Also, the measured current consumption in the sleep mode is 29 mA. According to the flowchart of the node, the total period (T) of the sensor node is 600 seconds (10 minutes) and the operating voltage of the sensor node is 5 V. Hence, the average power consumption (P_{avg}) of the sensor node is calculated using Eq. (1). Therefore, the average power consumption is equal to 7.96 mW.

$$P_{avg} = (P_{Active} \times T_{Active} + P_{Sleep} \times T_{Sleep}) / T \quad (1)$$

Fig. 8 shows the PPG signal that is captured from a patient’s finger in a sitting position. The PPG signal is filtered by a digital low pass filter and recorded by using the serial monitor program. During the experiment, the node samples the pulse oximeter sensor at a sampling frequency of 100 Hz. It is continuously monitored for 3 seconds. Fig. 9 illustrates the monitored physiological data of the patient on the BLE Terminal android Application. In this figure, the reading of a heartbeat is monitored with 60 bpm and is stored in a mobile phone for displaying. The readings of the patient’s body acceleration are displayed with -1 g in X, Y, and Z directions. Also, the readings of the angular velocity of the patient body are 180 degree/sec in X, Y directions and 45 degree/sec in Z direction. Thereby, these physiological data are an indication of patient status. In other words, a doctor can detect the status via a transmitted data from the patient through the Bluetooth low energy (BLE) of the node to a mobile phone of the doctor.

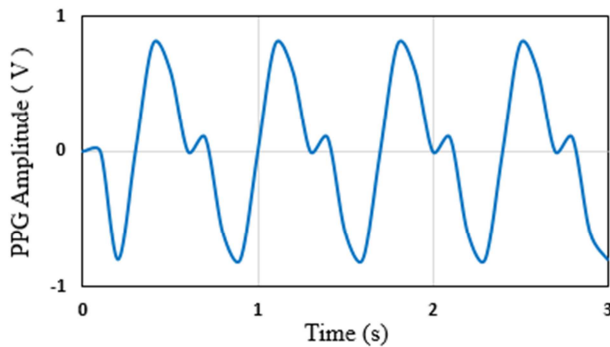


Fig. 8 The captured PPG signal from a patient’s finger

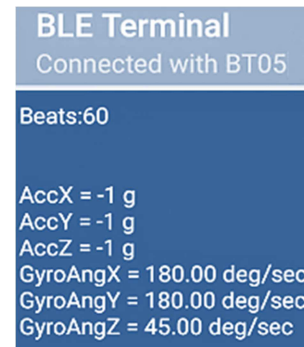


Fig. 9 Screen shot of the monitored physiological data

Finally, Table 4 illustrates a comparison between the proposed system and previous studies. In this work, the proposed sensor node has three physiological parameters, which are more than the nodes parameters in [11-13]. The Bluetooth low energy (BLE) wireless technology offers a higher range than the technologies in [11, 13]. On the other hand, the utilized energy harvester in the proposed system is a combination of two energy sources, which are “flexible photovoltaic (PV) panel and thermoelectric generator (TEG)”, while only one energy source “PV panel” was used in [11-13].

Table 4 Comparison between the proposed system and previous studies

Reference	[11]	[12]	[13]	This Work
Sensors	Temperature Sensor	Temperature Sensor	PPG Sensor and ECG Sensor	PPG sensor and MPU module
Number of Physiological Parameters	One (Temperature)	One (Temperature)	Two (PPG and ECG)	Three (Heartbeat, Acceleration, and Angular Velocity)
Wireless Technology	RF Transceiver 75 m	ZigBee 100 m	HC-06 9 m	BLE 100 m
Energy Harvester	PV Panel	PV Panel	PV Panel	Flexible PV Panel and TEG Module

5. Conclusions

This paper presents a self-sustainable medical sensor node for real-time healthcare monitoring. The node is powered by a hybrid energy harvester, which is a sustainable supply source during the running time of the node. The architecture of the harvester consists of a flexible photovoltaic panel to sense the irradiance of the sunlight with a thermoelectric generator (TEG) module to detect the temperature of human body. The flexible PV panel and TEG module are connected in parallel. The combination of the PV panel and TEG module are exploited to harvest the fast, sufficient, and more stable energy from the sunlight and the source of body heat. The proposed node continuously measures the heartbeats, accelerations and directions of a patient’s body. Finally, a physiological data of the sensor node is monitored on the BLE Terminal android application. In the future, multiple medical sensor nodes will be developed for a wireless body area network implementation.

Conflicts of Interest

The authors declare no conflict of interest.

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