Towards Batteryfree and Wireless Sensing for Personalized Ultraviolet Exposure Monitoring

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***Abstract*— A personalized wireless wearable system for measuring environmental information requires small size and light weight for portability. Body energy harvesting (e.g., kinetics, heat) is a promising solution to make the system work without battery, thus increasing the portability. In this paper, a personalized wireless sensing system powered by human body heat via thermal electric energy harvesting prototype is presented. Challenges caused by dynamic voltage supply, dynamic charging rates, and low-energy supply systems are identified and addressed. The experimental results show that this system can power a microcontroller and sensors while enabling wireless transmission of data. The thermoelectric generator with a heat sink is able to provide a steady charging voltage for 30–120 min.**

***Index Terms*— Energy harvesting, wearable sensors, self-power, UV exposure monitoring.**

I. Introduction

EXPOSURE science, i.e., the study of personal contact with toxicants occurring in the environment, fundamentally helps the mitigations of harmful exposures and ultimately improves the health protection of each individual [1]. For instance, workers exposed under diacetyl can result in severe lung diseases; a diacetyl exposure monitoring can help identify the locations of exposure, guide appropriate engineering controls, and select feasible breathing protections [2]. Current advanced exposure measurements utilize wearable devices targeting at unobtrusive and in-situ monitoring [3], [4]. However, their constraints are the limitation of battery capacity [5]. Due to a finite battery capacity (i.e., need frequent charging), a continuous and seamless exposure monitoring is hardly achieved.

Towards uninterrupted energy supply, self-powered (i.e., battery-free) wearables harvest and utilize energy from the exterior sources including heart [6], motion [7], sun light [8] and radio frequency [9]. Many existing self-powered wearable studies focus on human physiological signal (e.g., heat beat and blood pressure) monitoring [10], [11]. To our knowledge, this technology is rarely deployed for ubiquitous exposure sensing since the combination of exposure sensors and wireless communication is extremely power-hungry.

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In this paper, we explore the first self-powered wearable prototype in wireless personalized ultraviolet (UV) exposure sensing. Specifically, we are interested in indoor (e.g., disinfection lamp and industrial welding) and outdoor (e.g., sun light) UV exposure as it is strongly related to a variety of ocular and skin diseases including cataract, keratoconjunctivitis, dermatitis and melanoma [12]. Towards a self-powered, wearable and wireless monitoring system, the prototype is built upon a thermal electric generator (TEG) for human body heat harvesting, a supercapacitor for energy storing, and two RFduino microcontrollers for wireless data transmission.

The details of our development is discussed in the remaining of this paper organized as follows: Section II introduces existing mechanisms in energy harvesting; Section III presents an overview of the system with design considerations; Section IV and V illustrate the details of each main hardware, software component; Section VI evaluates the system feasibility in various situations. Finally, Section VII concludes the study.

II. Background

Energy harvesting, i.e., gathering energy from external sources, has been investigated as a potential solution to replace battery for long term energy autonomy. Existing energy harvesting techniques include ambiance and human based approaches. The ambiance based ones exploit environmental energies (e.g., sun light, wind power and radio frequency), which are powerful and yet intermittent. For instances, solar energy is hardly available in indoor environments; radio frequency power can be easily affected by distances [13]. Human based approaches utilize energy produced by human physiological features (e.g., body heat and physical motions [13]), which can provide sufficient energy for small electronic devices in both indoor and outdoor environments. Overall, the human induced power supply is a finer fit for a wearable personalized exposure monitoring system.

III. System Overview

Most of the human induced power is produced by either active or passive human motions. Limitations exist in both

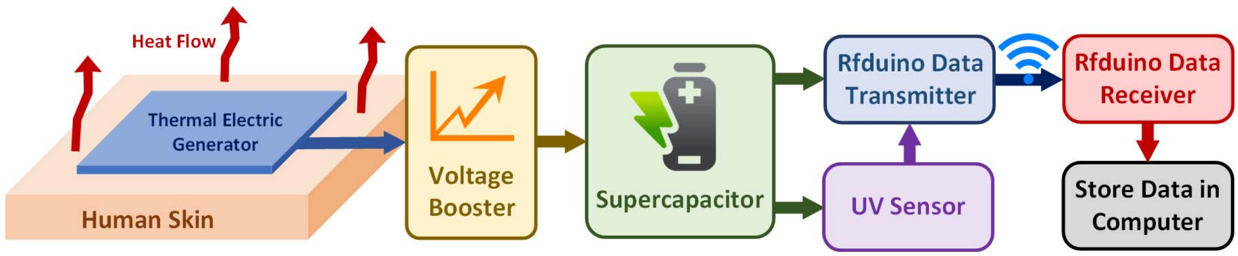

Fig. 1. The system architecture and data flow of the self-powered system. Energy is harvested by TEG from human skin and stored in the supercapacitor, which later will be used for powering UV sensor and RFduino transmitter.

mechanisms. The active motion (e.g., gait and activity) based energy harvesting is exclusive such that it is not applicable for disabled population. The passive motion based energy harvesting usually requires obtrusive or even invasive sensor deployment. For instances, a study utilizes a breath mask for producing respiration based energy [14]. According to Nanda and Karami [15], the energy produced by blood pressure is harvested by a sensor implanted into the blood vessel. Unlike the aforementioned motion based energy harvesting, body heat is a continuous and automatic motion-free feature of any individual which is highly accessible through any part of human skin. We hereby exploit the body heat as an inclusive and unobtrusive power supply for personalized exposure monitoring.

A. Design Considerations

In this prototype, we are required to consider current leakage across all modules due to the low power supply (μA supply). The current leakage must be significantly lower than the current supply. This implies that all the sensors and transmitters must operate on low voltages, current to minimize power consumption and optimize the system operation, which otherwise cannot function.

We also consider the dynamics in charging rate provided by the TEG and in the voltage supply from a constantly charging low energy capacity storage unit. The dynamic charging rate creates difficulties in predicting when there will be enough stored charge to power the sensors and the microcontroller. The dynamic voltage supply creates difficulties in predicting the source voltage at the time of a measurement taken by the sensors. If the source voltage is unknown at the time of a measurement, the accuracy of the measured data may be compromised.

B. System Architecture

The entire system architecture is shown in Fig. 1. The TEG on the human skin is heated by the body heat. It creates a voltage which is then amplified by the voltage booster and charges the supercapacitor to hold enough periodical power for supporting a RFduino data transmitter and a UV sensor. The transmitter wirelessly sends the collected sensor data to a RFduino data receiver inserted in the USB drive of a computer which reads and stores the live feed of UV exposure.

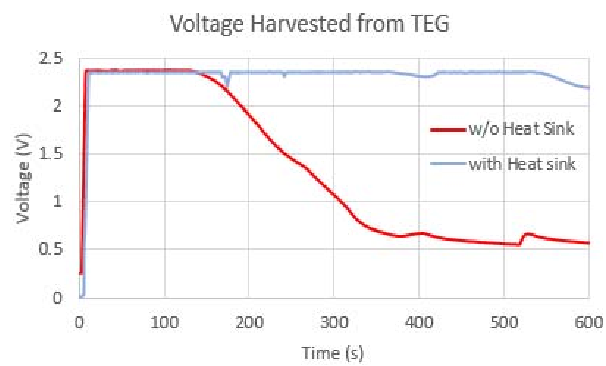

Fig. 2. Voltage harvested using $LTC3108$ without load connected. Note that the user movement caused the voltage to decline at end of reading with heat sink.

IV. Hardware Design

A. Characterization of TEG

This self-powered wireless sensing system generates its power by converting excess heat to electricity, which is through the TEG device. All power consumed by the system is generated by the TEG. The TEG relies on the spatial temperature difference between the cold and hot components [16]. This component produces only a small amount of voltage from the temperature differences created by contact with the human body. If the heat sink is attached, the heat dissipation on the cooling element is greater, allowing the TEG to maintain a larger temperature difference and higher voltage for longer periods of time. As depicted in Fig. 2, the voltage drops rapidly after 100s without a heat sink, whereas the voltage remains stable with a heat sink. Note that the voltage decline at end of reading with heat sink is because of the user movement.

B. Electronic Modules

1) Voltage Harvester: To harvest the energy produced by the TEG, we use a DC/DC converter $LTC3108$ [17] to boost the input with a minimum of 20 mV and charge the supercapacitor. The output voltage is set to 2.35 V, and the wake up circuit is powered by the Power Good Output (PGD out) which triggers when the output voltage reaches 2.17 V meaning the supercapacitor is charged enough to transmit data. The $LTC3108$ can also be set to other voltages as 3.3 V, 4.1 V, or 5 V. However in these settings, the current

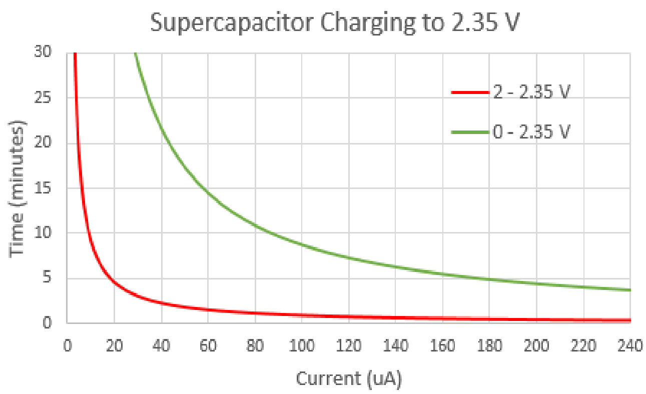

Fig. 3. Charging the 22 mF Supercapacitor from 0 to $2.35V$ versus 2 to $2.35V$. Charging from 0 to $2.35V$ takes much more time than from 2 to $2.35V$.

output is lower, charging rates are decreased, and the wake circuit becomes much less reliable.

2) Energy Storage: The energy storage unit of this system is a 0.022 F 5.5 V supercapacitor [18]. It is found that if the energy capacity of the storage unit is too high, such as for a 1 F supercapacitor it will take hours or even days to charge the capacitor to the desired voltage given static charging rates of less than $100\mu A$. However, if the storage is too low there will not be enough energy stored to power the transmission and sensors in the system. The capacitor used here has a current leakage of only $10-200$ nA at any given time during the tests measured.

3) Microcontroller Transmitter and Reciever: The RFduino [19] is a microcontroller that uses low power Bluetooth for wireless connection. This controller was chosen here due to the low voltage requirements ranging from $2.1-3.6$ V, and ultra-low power sleep state capabilities. The typical supply voltage is $3V$ with the transmit/receiver current of $12mA$ and ARM CPU running current of $4mA$. We use two RFduinos in this system including a transmitter and a receiver. While transmitting, the device consumes $12-18$ mA, but in this system the RFduino transmitter only requires to be on for a few milliseconds after being charged for a much longer period of time. While not transmitting, the device is turned off to maximize the amount of power saved. During the time that the RFduino is turned off, the system consumes $3-8\mu A$ passively due to leakage between all components. However, while the TEG is being warmed this cost is counteracted by the charging current. This means that if the system is left without charging for an extended period time it will take much longer to charge back to the operating voltage, as shown in Fig. 3, this would be the most extreme situation for charging rates. While the energy harvesting system is providing at least $40\mu A$ of charging current, as during peak performance, there may be between 30 and 60 seconds for every transmission, unless the wake circuit does not work properly. This could mean a single wake cycle triggered more than one transmission, or several failed wakes have taken place, which will be explained in Subsection IV-C in details. In these cases it can take anywhere between $5-15$ minutes to charge and/or transmit data.

On the other end, the RFduino receiver, which is wirelessly connected to the RFduino transmitter, tracks the time of receiving each data packet. This will notify the user on the computer if the data has not been received in the past 20 minutes such that some errors may exist in the charging of circuit or waking up the circuit. These errors can be easily fixed by resetting RFduino transmitter or allowing the TEG to cool for a short period of time.

4) Sensors: The personalized sensors attached to the circuit are the tools that collect the desired data for the system. We use the internal temperature sensor offered by the RFduino to measure temperature, and externally the $ML8511$ [20] to measure UV intensity. The operating voltage of $ML8511$ is $2.7-3.6V$ with a typical voltage of $3.3V$, and the typical supply current is 300μA. Based on power constraints, theoretically, other sensors could be attached, however in practice, the designer must account for the design considerations explained in Section III.

C. Wake Up Control

This system utilizes a wake up circuit to trigger when the capacitor is charged enough to power the circuit. Using this method allows the system to compensate for a dynamic charging rate, rather than using a clock to time regular intervals between transmissions. In addition, it is found to consume much less power than the low-powered clock in the RFduino, which is found to drain current at 1.32 mA constantly while in the sleep position instead of $2-4\mu A$ current leak from the RFduino in the off position.

The wake circuit consists of a $10\mu F$ capacitor that bridges the Power Good Output (PGD out) from the $LTC3108$ to pin 5 on the RFduino, and a pull down 3 $M\Omega$ resistor.

The capacitor delays the voltage from the PGD output. Without the capacitor the wake pin will sense the voltage, before the voltage is high enough, to trigger the waking program causing the circuit to consume power as if it transmitted data, but failed to send any data successfully, which will be referred to as a failed wake. The addition of the capacitor here makes the failed wake scenario much less likely, however there is still a chance that the circuit will get stuck in a failed wake loop charging and discharging for minutes at a time. To counteract this we implement a protocol in the software.

The 3 $M\Omega$ pull down resistor prevents false activations of the wake pin triggered randomly by air, or movement of the circuitry touching pin 5, we will refer to these false activations as false wakes. The resistor prevents all false activations of pin 5 caused by outside noise, however false activations still take place sometimes during the time after the PGD output is activated if the voltage does not dissipate quickly enough from the capacitor, this is limited by resetting the pin after activation and a 1 ms delay within the program. The resistor makes the system much more reliable, and since there is enough resistance that there is not a significant amount of leakage current, or excess current flow when the PGD output is activated, there are no significant losses incurred by the resistor.

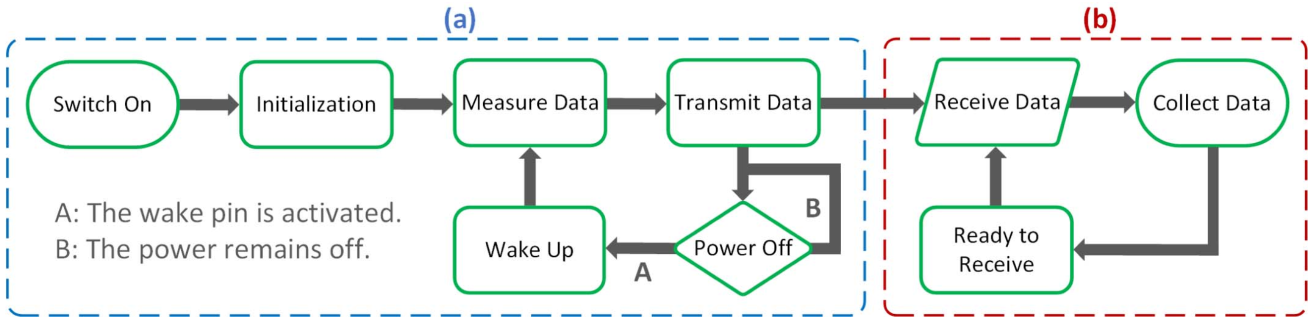

Fig. 4. The overview of the software control diagram for the RFduino data transmitter and receiver. First the user must turn on the device manually, then the RFduino initializes the RFduino Gazelle (GZLL) protocol via Bluetooth and connects to the host of RFduino data receiver.

V. Software Design

A. RFduino Data Transmitter

The RFduino data transmitter is attached to the isolated circuitry which is powered by the TEG. Its control diagram is shown in Fig. 4 (a). Firstly, the user must turn on the device manually and then the transmitter initializes the RFduino Gazelle (GZLL) protocol via Bluetooth and connects to the host of RFduino data receiver. During this initializing stage, the controller also configures the input, output, and wake pins. Once the device is initialized, it then proceeds to measure data from the sensors that have been configured to the RFduino.

In this scenario, during the data collection step, the device first measures the temperature given by the internal sensor and stores this in a data structure to be ready for transmission. Then the device activates the source pin for the $ML8511$ UV sensor and waits for 1 ms low-power delay to ensure voltage stability. After the short delay, the output from the sensor is measured, and processed to finally extract the UV intensity. Immediately after the data is collected, the source pin for the UV sensor is deactivated, and then the structured data is transmitted in a single pulse. The transmitter then automatically turns off until the wake pin is activated. In this part of the software, we account for a current leak due to the $ML8511$ UV sensor by ensuring that the pin connected to the VCC+ of the sensor is only activated while the device is performing a measurement. Since this device has a passive leak of more than a few μA, it is necessary for the prototype to function with a temperature difference across the TEG that is large enough to counteract the additional leakage from this sensor.

The wake up protocol in this program allows the transmitter to minimize the time awake, and avoid false wakes, which increases the efficiency of the system but this does not address all the issues remaining. The wake up function turns on the receiver and reactivates the main code every time there is a high voltage applied to the wake pin. The wake up control is not completely reliable, so we utilize the functionality of RFduino data receiver to notify us if data has not been received recently (i.e., within the past 20 minutes). This protocol is useful because failed wakes are common, and sometimes the temperature difference on the TEG is very low and charging slows down to less than $5\mu A$. This tells the user to reset the system, or check the charging mechanism for anything that may be causing issues.

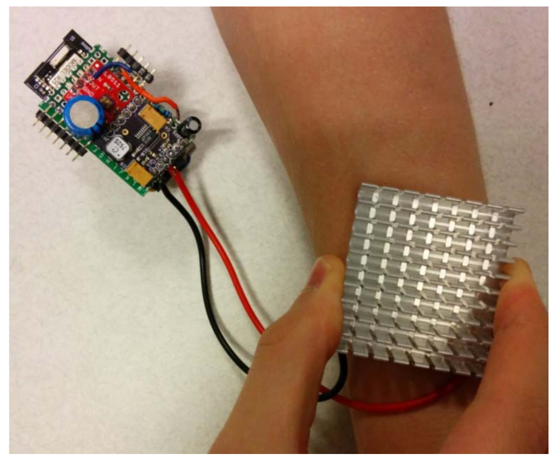

Fig. 5. Heating TEG on the arm. The other side of the TEG is cooled by the ambient air through the heat sink.

B. RFduino Data Receiver

The RFduino data receiver is connected to a computer for real-time data collection. The software control diagram is presented in Fig. 4 (b). First, the receiver initializes the GZLL protocol, and then begins the main loop code. At the beginning of each loop, the host device measures the current time. Then the device is ready to receive data, and at this point it will either receive data, or not receive data. If the device receives data, it will then display the data on the computer, then repeat the loop. If the device fails to receive data, it will check how long it has been since data was last received, and notify the user on the computer if it has been longer than 20 minutes, then repeat the loop.

VI. Experimental Study

The main goal of this study was to confirm the feasibility of wireless sensing powered by body heat, and to explore the various challenges of this type of system. The first study is the TEG test that observes the characteristics of the TEG on the human body. In the experiments with the system prototype, the TEG was heated on the arm, as shown in Fig. 5, or by

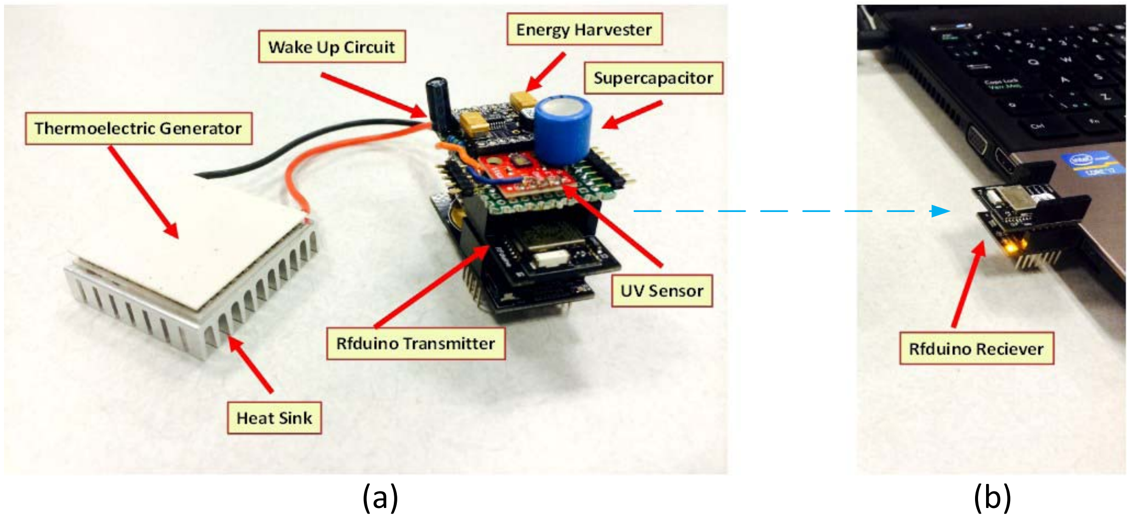

Fig. 6. Personalized ultraviolet exposure monitoring system prototype, (a) Main system including TEG, heat sink, wake up circuit, supercapacitor, energy harvester, UV sensor, and RFduino transceiver. (b) RFduino receiver connected to a computer to collect data.

putting a hand on the hot side of the TEG. The other side of the TEG is cooled by the ambient air through the heat sink. During the experiments, it was important to monitor the voltage level with a voltmeter on the output at all times to observe the behavior of the system. The prototype shown in Fig. 6 shows that there is also RFduino 2 receiving the data and porting it to the computer.

A. TEG Test and Characterization

The purpose of this test initially is to understand possibilities of using the TEG and gauge the potential of the TEG powered by human body heat. In this study, the TEG creates a potential difference based on the temperature difference between the hot and cold sides of the TEG [16]. This temperature difference can vary greatly depending on factors such as ambient room temperature, initial temperature of the TEG, body contact location, body warmth, and heat dissipation on the cooling element. For typical usage of this $40\ mm \times 40\ mm \times 3.6\ mm$ TEG, it is found that voltage between 10 and 220 mV would be produced without the heat sink, with the time response as shown in Fig. 7. In Fig. 7, there are three different trails of data to demonstrate some possibility how different factors can change the functionality of the TEG. The first trial is heating the TEG on the arm. In this trial there is a lot of initial noise from movement, so the real measurements start at around 50 s into the data collection. In future studies, this will be compensated by securing the TEG in an arm band around the arm. In the next two trials, the TEG was heated by the hand on the hot side of the TEG rather than the arm. It is noted that there is a wide range of possible voltages due to the factors earlier described, and the supply current produced varies similarly to the voltage.

The typical voltage created during similar tests when the heat sink is applied is between 15 and 250 mV. Under most conditions, such as inside temperature controlled buildings, the TEG will not dissipate heat on the cool side at the same rate as the cool side is heated, therefore after long periods of time the temperature difference will shrink and in turn, the charging rate will decrease.

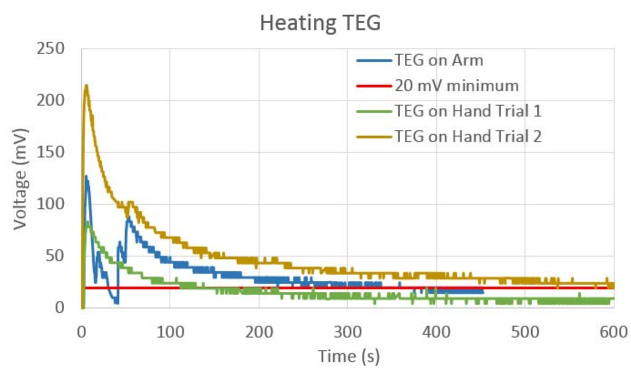

Fig. 7. TEG voltage output after applied heat with arm and hands. The measurement from arm starts at around 50s because of the initial noise from movement. The voltage obtained from hands is higher than the one obtained from the arm.

B. System Integration

The prototype is designed such that it integrated each module together into a single unit that is small enough to fit in a pocket. As described previously there are two types of data collected from two different sensors, the thermometer on the RFduino, and the external UV sensor. Fig. 8 shows two different occasions where data is collected. The first, where the RFduino is next to a computer fan blowing warm air onto the RFduino. The second, the RFduino is in the same room still but away from the warm air current from the computer. The data is also collected for the UV sensor, but the sensor is not functioning properly in this context, which will be improved in the future.

C. System Evaluation and Analysis

In the first study we can tell that there is a difference between the separate trials, however it is difficult to pinpoint

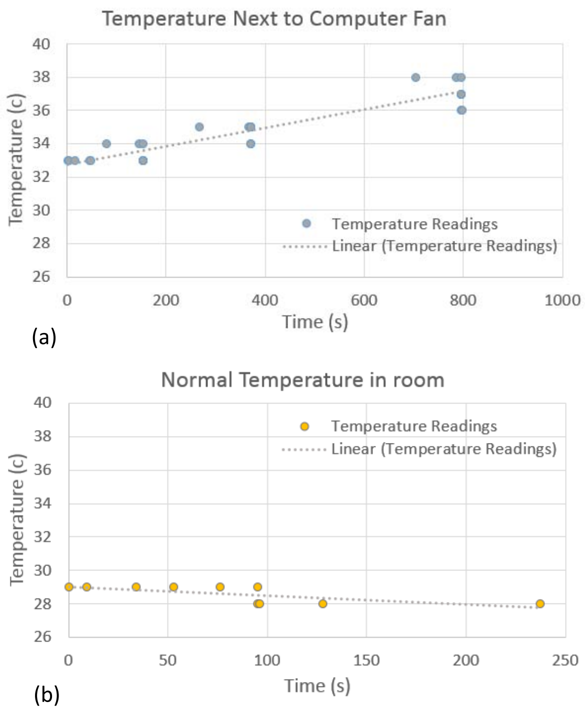

Fig. 8. Temperature data collected in the second experiment. (a) Temperature increase linearly versus time when the temperature sensor is located near a computer fan. After about $800s$, the temperature increases about 5 degrees. (b) Temperature decrease a little versus time when the sensor is located in an office room.

the exact factors that create these conditions. In the second on hand trial, the voltage is much higher than the other two trials. This is because the initial temperature of the TEG is lower in this experiment due to the TEG cooling for more than an hour prior to this measurement, whereas data from the other trails had just been collected minutes before the measurements and the period of time for cooling is only a few minutes. We noticed that heating the TEG with the hand is overall more effective than the arm, because there is a better heat connection between the hand and the TEG than the arm. With the installation of an arm band that integrates a heat sink, the arm is expected to be more effective since it is warmer than the hand.

In the TEG test, we can also see that the voltage drops below the minimum required voltage for the $LTC3108$ of 20 mV after only 5 minutes without the heat sink. When the heat sink is attached to the TEG, the voltage does not drop this low typically, but it gets very close and the charging rate can decrease dramatically after an extended period of time $(30 - 120$ minutes) causing problems with the wake up circuit.

The data collected with the temperature sensor conclusively tells us that there is a trend that the sensor by the computer fan warms up, while the other sensor mostly remains at a constant temperature. This proves that this is feasible to power the RFduino using excess human body heat. However, this presents many possible challenges that must be considered in the development in the future. The time between the measurements shown in Fig. 8 may vary greatly between 0 and 300 seconds in this example. Note that where there are multiple readings at the same time, these are false wakes that draw more current than necessary. After these false wakes the operating voltage is lower than it would be otherwise, sometimes as low as 2 V. This change in voltage clearly changes the temperature read by the sensor by 1 to 2 degrees C due to the dynamic voltage supply, the accuracy of the data is compromised.

The data collected from the UV sensor, in current the stage is meaningless because the voltage supply is not high enough. The data collected is almost identical in direct sunlight, and in complete darkness. If the voltage supply is high enough it would still face issues in accuracy just as the temperature sensor, because the UV sensor assumes a stable voltage supply that is not dynamic to measure the UV intensity.

D. Usability

Because the TEG makes direct contact with human skin, it is important to make sure that the system will not cause any health problem related to skin temperature decrease when harvesting energy from human body. Researchers found that TEG is safe to use for a long time. Specifically, Leonov *et al.* [21], [22] integrated TEG into shirts and attached TEG to wrist to harvest energy from human body in daily life. We also conducted a usability study, three subjects have worn TEGs on the arm and leg for 10 hours in one day, and none of them reported any uncomfortableness. Therefore, wearing TEG on arm, leg, or anywhere of human body for a long time is less likely to cause any health issue related to skin temperature decrease.

VII. Conclusion and Future Work

This study brings all elements together for human powered sensors for ambient monitoring, and characterizes the behavior of the system from power generation to collecting data from sensors.

There will need to be special considerations for the dynamic source voltage. As well as special consideration for current leakage across all components and study on how the system works with different types of sensors. In the future work, we will work towards increasing the working voltage of the system and compensate for the dynamic voltage to make the UV sensor functional, and in addition explore how more factors such as initial temperature, and ambient temperature of the environment of the TEG affect the performance in this system.

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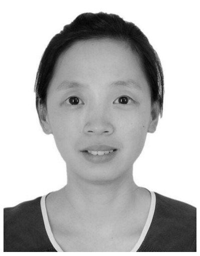

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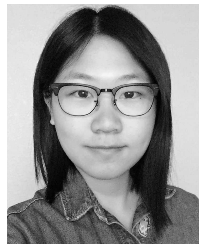

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