HARVESTING BODY HEAT FOR REMOTE PULSE SENSOR MONITORING

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ABSTRACT

With the evolution of technologies, energy consumption management has become a paramount concern. Energy harvesting is employed to recharge, supplement, or replace batteries in systems where their use is impractical, costly, or dangerous. Ambient energy sources such as light, temperature differentials, mechanical vibrations, or RF signals can be converted into electrical energy using a transducer. These energy sources are ubiquitous and can be harnessed to power electronic devices.

In this article, we focus on the pulse sensor, which plays a crucial role in monitoring heart rate and displaying real-time corresponding graphs. The objective is to remotely monitor patients' cardiac health while minimizing energy consumption. To achieve this, we explore an innovative solution that involves generating thermoelectric energy from body heat to power the back electrodes of the pulse sensor. This approach reduces dependence on external power sources and optimizes energy efficiency in the context of telemedicine.

By combining ambient energy harvesting with the utilization of thermoelectric energy, we offer a promising solution to enhance remote heart rate monitoring. This groundbreaking approach allows us to leverage the benefits of telemedicine while ensuring efficient energy utilization. The article delves into the details of this technology and highlights its potential in the realm of connected health.

Keywords: *Pulse Sensor, Telemedicine, Thermoelectric Energy, Seebeck, Peltier*

1. INTRODUCTION

Following the COVID-19 pandemic, there is a widespread acknowledgment of the necessity for remote solutions in virtually all processes, particularly in critical areas like healthcare where human intervention is indispensable. In response to this, we have conceptualized a solution for remote measurements utilizing advanced sensor technology.

Even before the pandemic, remote monitoring of cardiac patients has been a research focus that has often been the subject of several research works. The majority of solutions are based on wireless sensor networks [16][17][18], and as we all know, the problem with these solutions is the management of energy consumption by these sensors, given their very small size.

Utilizing the body's own heat through thermoelectric devices presents a promising avenue, tapping into thermoelectric generators to transform the body's natural warmth into usable electrical energy. These generators, akin to the mechanics of a thermocouple, convert heat into an electric charge.

There are diverse methods in play for capturing this bodily warmth using thermoelectric devices. Some techniques involve the direct application of thermoelectric sensors onto the skin to gauge bodily heat, while alternative approaches employ these sensors to detect emitted body heat from a distance.

The possible applications stemming from this concept are indeed manifold. They encompass an array of scenarios, ranging from health monitoring and fitness tracking gadgets to safety measures designed for the elderly and those with restricted mobility. Furthermore, these applications extend to access control systems and even environmental monitoring setups.

It's worth noting that the efficiency of these thermoelectric generators remains modest,

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translating to a limited yield of electrical energy. Thus, it becomes imperative to implement a suitable energy management circuit to store and optimize the electricity generated by these thermoelectric modules.

Additionally, paramount consideration must be given to the well-being and comfort of individuals wearing these thermoelectric sensors. The imperative is to craft devices that seamlessly meld with human form, accounting for temperature variations, insulation concerns, and seamless integration with other electronic components.

In the context of our research, our primary objective hinges on streamlining the medical diagnostic process, all while curbing the energy consumption tied to pulse sensor technology. Presently, the monitoring of cardiac health predominantly rests upon pulse sensors, which continually gauge heart rate and relay real-time data. Yet, these sensors demand a consistent power source, a need that can potentially give rise to significant energy consumption, especially in remote patient monitoring scenarios.

2. HARVESTING BODY HEAT USING THERMOELECTRIC DEVICES

2.1. Different Approaches to Body Heat Harvesting

Various approaches are employed for body heat harvesting using thermo-electric devices. Some methods involve the use of thermo-electric sensors directly attached to the skin to detect body heat, while others utilize thermo-electric sensors to detect body-emitted heat remotely [1]. These sensors, sensitive to temperature variations, are integrated into wearable devices like smart bracelets or clothing, enabling continuous monitoring of body heat.

2.2. Diverse Applications of Body Heat Harvesting

The potential applications of body heat harvesting through thermo-electric devices are extensive. They encompass health monitoring, such as tracking body temperature or detecting temperature variations indicating potential health issues. These devices can also be used in the realm of sports and fitness, measuring body heat during physical activity. Furthermore, they can be integrated into security devices for the elderly or mobility-impaired, monitoring their body temperature and alerting to abnormal changes. Lastly, body heat harvesting can also find use in access control systems or environmental monitoring for security applications.

2.3. Energy Consumption Reduction

Thermoelectric generators efficiently convert body heat into electrical energy, contributing to sustainable utilization of energy resources and reduction of ecological footprint. This innovative approach optimizes energy efficiency while enhancing healthcare quality.[2]

It is crucial to acknowledge that the efficacy of thermoelectric generators in reducing energy consumption and enhancing cardiac monitoring offers exciting prospects for the future of medicine and technology.

3. PRINCIPLES OF OPERATION OF THERMOELECTRIC GENERATORS

The concept of harnessing body heat using thermoelectric devices stems from a highly promising notion that taps into thermoelectric generators (TEG in Figure 1) to transform the heat generated by the human body into usable electrical energy. These generators make use of the principles of the thermoelectric effect to achieve this conversion. The thermoelectric effect, a fundamental physical phenomenon that links temperature differentials to electric currents, forms the bedrock of this transformative process, facilitated through the use of carefully selected thermoelectric materials.

When a thermoelectric material is subjected to a variance in temperature, it triggers a migration of electrons from the warmer region to the cooler one [3]. This motion of electrons results in the creation of an electric current, one that can be effectively harnessed to power electronic components like sensors. Therefore, by capturing and utilizing the warmth generated by the human body, thermoelectric devices ingeniously generate electricity, thereby adhering to the principles of energy efficiency and environmental friendliness.

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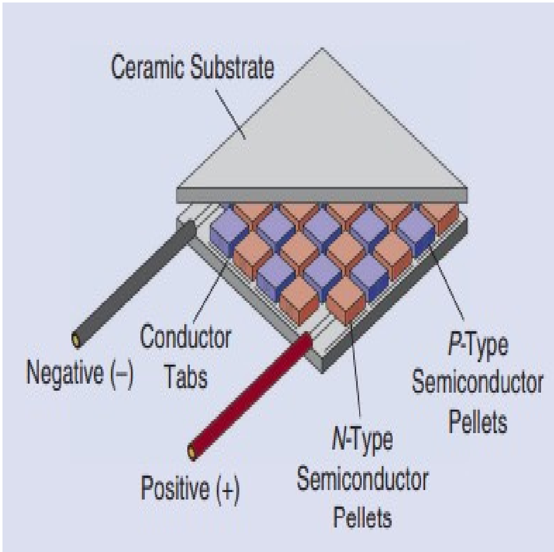

Figure 1. The TEG construction [4]

3.1. Unveiling the Seebeck and Peltier Effects

The Seebeck effect, sometimes referred to as the thermoelectric effect, comes into play when two dissimilar conducting materials are exposed to a temperature gradient. This phenomenon leads to the generation of an electric voltage across these materials, consequently generating an electrical potential difference between their respective sides. Upon connecting these sides within a circuit, this voltage differential brings about the flow of an electric current. This electric voltage is commonly known as the thermoelectric electromotive force (TEMF) or thermoelectric voltage [7].

The Seebeck coefficient (α), a crucial parameter in this context, quantifies the voltage generated per unit temperature gradient between two materials. Its formulation is represented by the equation: α = ΔV / ΔT [6], where ΔV signifies the potential difference generated and ΔT represents the temperature gradient.

Closely interconnected with the Seebeck effect is the Peltier effect, which manifests when an electric current traverse the junction between two distinct conducting materials characterized by varying temperatures. If this current flows from a lower-temperature material towards a higher-temperature one, it prompts the transfer of heat, causing a cooling effect on the cooler side and a heating effect on the warmer side of the junction. Conversely, when the current's direction is reversed, the heat transfer mechanism also reverses, leading to warming on the cooler side and cooling on the warmer side.

The Peltier coefficient (π), a counterpart to the Seebeck coefficient, quantifies the heat absorbed or released per unit electric current passing through a junction. It is determined by the equation: π = Q / I, where Q denotes the transferred heat and I signifies the electric current [10].

Thermoelectric generators (TEGs) ingeniously harness both the Seebeck and Peltier effects in tandem, utilizing them to convert the temperature differential between the two sides of the device into a stream of electricity. The Seebeck effect instigates the generation of an electric voltage due to the temperature disparity, while the Peltier effect actively sustains this temperature disparity by facilitating the transfer of heat from one side to the other in alignment with the direction of the electric current. This adaptive approach empowers thermoelectric generators to effectively convert heat into electricity or provide thermoelectric cooling, with the configuration and application determining the choice.

In essence, thermoelectric generators proficiently capitalize on the Seebeck effect to engender an electric voltage and the Peltier effect to uphold the vital thermal gradient requisite for this process of energy conversion.

It's important to highlight that utilizing series and parallel connections for TEGs can be employed to enhance both voltage levels and output currents. This strategy capitalizes on the intrinsic composition of TEGs, characterized by an array of thermocouples. In cases where a TEG comprises "n" thermocouples interconnected in both series and parallel fashion, alongside thermal connections, the resultant open circuit voltage can be mathematically expressed as follows:

$$V_{oc} = S \times \Delta T_{TEG} = n \times \alpha (T_{HJ} - T_{CJ}) \quad (1)$$ [5]

α and S stand for the Seebeck coefficient of a thermocouple and a TEG, respectively. ΔTTEG signifies the temperature difference, while THJ and TCJ denote the temperatures of the hotter and colder sides, respectively. Additionally, the TEG's output power can be computed as follows:

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$$P_{TEG} = \frac{\alpha^2 \Delta T_{TEG}^2 . R_L}{(R_{TEG} + R_L)^2} \quad (2)\ [5]$$

RTEG represents the internal resistance of the TEG, and RL signifies the load resistance. The optimal point for achieving the highest power transfer from the TEG's source to the load occurs when RTEG equals RL.

4. HARDWARE DEVELOPMENT

Throughout our comprehensive study, we conducted experimental tests (Figure 2) to assess the feasibility of an innovative system aimed at generating thermoelectric energy from body heat to provide real-time power to the rear electrodes of the pulse sensor. In implementing this device, close collaboration with a high-precision pulse sensor was integral, designed specifically for reliable cardiac signal detection.

To ensure a continuous power supply to the pulse sensor independent of external energy sources, we opted for the integration of carefully positioned thermoelectric generators on the human arm. Strategically placed to harness the temperature gradient between the human body and the ambient environment, these generators played a pivotal role in harnessing body heat for conversion into usable electrical energy. Through this approach, we could maximize conversion efficiency and optimize electrical energy production while adhering to safety standards suitable for medical use.

To achieve this energy transformation, the thermoelectric generators were linked to the LTC3108 voltage converter. This sophisticated electronic component was deliberately selected to convert the voltage generated by the thermoelectric generators into electrical power suitable for powering the pulse sensor. The LTC3108 demonstrated its capacity to maintain a stable and reliable voltage output, thereby ensuring the proper operation of the sensor across various environmental conditions.

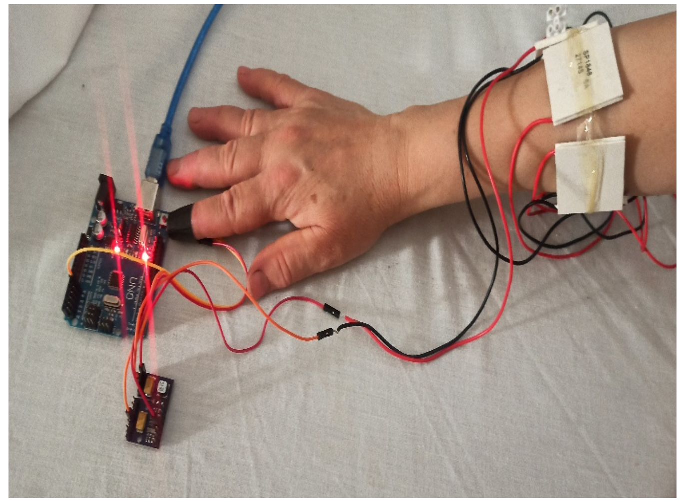

Figure 2. The actual implementation of our solution

4.1. Pulse Sensor: XD-58C Module

The use of sensors in various fields [15], offers many advantages to humanity, especially in conditions where humans cannot react. There are several types of sensors [15].

In our study, we delved into the utilization of the XD-58C module (Figure 3), a specific optical heart rate sensor, for our experimental endeavors. This module features a configuration comprising an infrared LED that emits light onto the skin and a photodetector that captures variations in reflected light resulting from blood flow.

By harnessing the principle of photoplethysmography (PPG), our optical sensor measures changes in light absorption by skin tissues based on fluctuations in blood volume. As the heart beats, the volume of blood within blood vessels varies, leading to alterations in the absorption of infrared light by these vessels [8].

The photodetector of the XD-58C module converts these variations in reflected light into an electrical signal, which is then processed to extract real-time heart rate data. The sensor's performance relies on the sensitivity and precision of the module, as well as the quality of signal processing.

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A significant characteristic of this optical sensor is its user-friendly and non-invasive nature. It can be seamlessly integrated into wearable devices such as watches or connected bracelets, providing users with the capability to monitor their heart rate during physical activities or at rest.

Through our collaboration with the XD-58C module, we were able to conduct advanced experiments concerning heart rate measurement. This optical sensor played a pivotal role by delivering accurate and reliable measurements, thereby contributing to the enhancement of our overall heart rate monitoring system.

Ensuring the protection of the exposed circuitry of the pulse sensor is of utmost importance to prevent sweat from your fingers or earlobe (or any other location) causing signal interference or a short circuit. In this regard, we have employed hot glue, which offers the convenience of easy removal or reworking should you decide to relocate your pulse sensor.

The use of hot glue provides a flexible solution that doesn't compromise the sensor's functionality. Its adhesive properties allow for secure attachment without the risk of signal disruption. Additionally, it offers the advantage of easy repositioning if needed.

This method also allows for adaptability and modification, which is particularly useful when adjustments to the pulse sensor's placement are required.

By applying a controlled amount of hot glue, you can effectively safeguard the pulse sensor's sensitive components from potential hazards such as moisture and external contact. This protective measure serves to maintain the sensor's accuracy and reliability over extended periods of use.

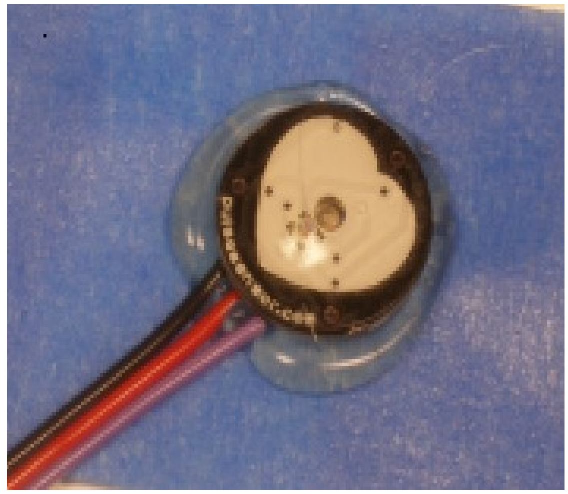

Figure 3. Pulse sensor (XD-58C)

4.2. LTC3108: Boost Converter

We seamlessly incorporated the LTC3108 circuit (Figure 4) into our optical pulse sensor system. The LTC3108 stands as a pivotal DC-DC circuit, instrumental in amplifying and transforming the electrical energy generated by the thermoelectric generator (TEG) into a suitable voltage to power our pulse sensor [9].

Our selection of the LTC3108 hinged upon its efficient performance and its ability to maximize the available power derived from the temperature difference within the human body. Through its proficient conversion mechanism, it ensures a stable and regulated voltage output, thereby guaranteeing that the cumulative power stemming from the temperature difference within the human body is ample to drive our pulse sensor.

The step-up DC-DC circuitry within the LTC3108 boasts an elevated level of efficiency, thereby minimizing energy losses and fine-tuning the utilization of the accessible energy. This component assumes a critical role in the conversion of thermal energy into a reliable and regulated power source tailored for our optical pulse sensor [11].

By strategically integrating the LTC3108 in tandem with the TEG and other integral components of our system, our findings substantiate that power exceeding 63 µW can be harnessed at a temperature of 22°C. This generated power notably surpasses the requisite threshold to ensure the optimal performance of our pulse sensor.

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Ultimately, the seamless integration of the LTC3108 into our optical pulse sensor system has markedly contributed to optimizing the energy efficiency of our overarching system, consequently assuring a dependable and precise operational framework for our pulse sensor.

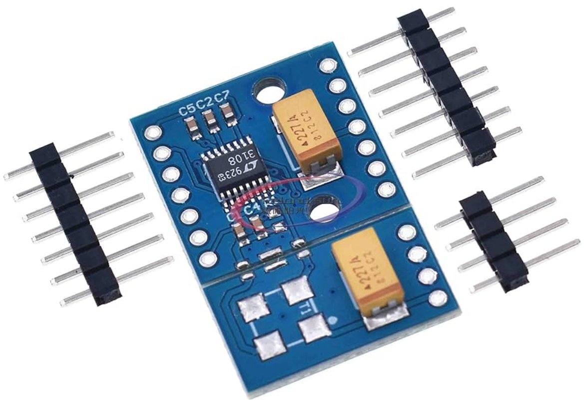

Figure 4. LTC3108 circuit

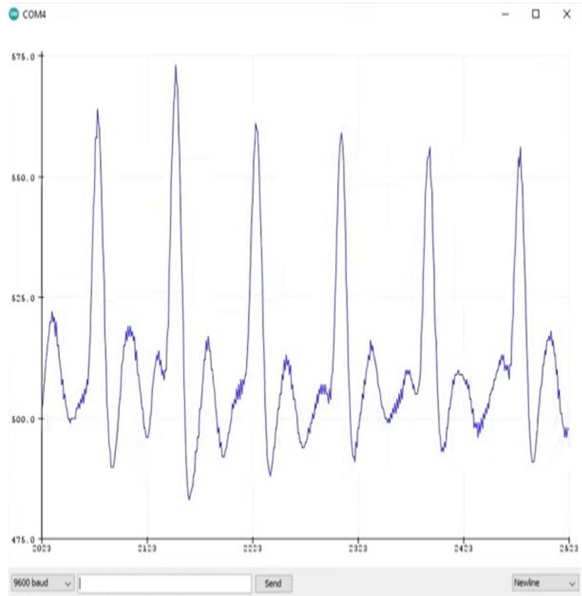

Figure 5. The resulting graph

5. EXPERIMENTAL RESULTS

Our experiments were meticulously conducted in a controlled laboratory environment. Real-time data collected through the pulse sensor was carefully gathered and recorded using the Arduino platform. The same platform was also employed to generate a comprehensive graph that accurately represented the real-time heart rate.

The data analysis revealed promising outcomes, highlighting a clear correlation between subjects' cardiac activity and the production of thermo-electric energy. The graph generated by the Arduino provided a detailed representation of the real-time heart rate, serving as a valuable tool for analyzing system performance and identifying avenues for enhancement.

5.1. Graph Description and Analysis

The Pulse Sensor is commonly integrated with Arduino boards to measure an individual's heart rate. It detects fluctuations in the amount of light passing through the skin, which corresponds to the heartbeat. The sensor generates a series of analog values that fluctuate in sync with the heart's pulsations. Subsequently, the Arduino converts this analog signal into digital values and can visually represent it through a graph (Figure 5).

The x-axis (X) denotes time, with each time unit corresponding to a sensor reading. As time progresses, the graph displays successive heartbeats. On the y-axis (Y), the amplitude of the signal registered by the sensor is reflected. A stronger pulse results in a higher amplitude of the signal.

The graph's shape mirrors the fluctuations of light through the skin captured by the pulse sensor. It showcases regular fluctuations and peaks. Each peak corresponds to an identified heartbeat sensed by the sensor. The height of these peaks depends on the intensity of the signal detected at each heartbeat.

The waveform of a pulse sensor portrays the variations in the electrical signal generated by the sensor in relation to the heart's beats. This waveform is characteristic and mirrors the changes in pressure within blood vessels with each heartbeat.

Typically, the pulse sensor's waveform takes the form of a curve that sharply rises with each heartbeat and then descends until the next beat. Each peak on the curve corresponds to a heartbeat. The interval between these peaks determines the time interval between each beat,

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allowing for the calculation of the heart rate in beats per minute (BPM).

While slight variations in waveform might occur based on the sensor's placement, the type of sensor used, and the individual's physiological traits (such as blood vessel elasticity), the waveform usually remains consistent and characteristic. This facilitates precise and reliable measurement of the heart rate and continuous monitoring of an individual's cardiac rhythm.

After comparing with the graph obtained by our solution [12], inspired by the two works [13][14], which was based only on a simulation without physical implementation, we obtained satisfactory results.

The major advantage of this solution is its low cost compared to other solutions [17][18] found in the literature.

6. CONCLUSION

The proposed solution was an improvement of our simulated solution in our previous works.

Our experimental tests have demonstrated the viability of our innovative approach to real-time powering of the pulse sensor using thermoelectric generators and the LTC3108 voltage converter. The obtained results are promising and open up new perspectives in the field of connected health and sustainable energy management of medical devices.

This promising approach could contribute to reducing reliance on external power sources and optimizing the energy efficiency of medical devices, while enhancing patient autonomy and comfort in the context of telemedicine.

This proposition is a beta version of our solution that will be enhanced in our upcoming works to achieve a low-cost and more efficient solution in terms of optimizing energy consumption to the maximum.

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