Hybrid Powered Non-Invasive Wearable Glucometer for Continuous Glucose Level Monitoring

A.G.M.M. Thilakarathne, N.G.L.D. Madhumal, S.K. Jaslin, and A.I.S. Juhaniya

Abstract Continuous glucose monitoring (CGM) is essential for effective diabetes management, yet most commercial devices depend on invasive sensors and frequent battery charging, limiting usability and comfort. This paper presents the design and development of a hybrid energy-powered wearable glucometer capable of continuous, non-invasive glucose monitoring. Non-invasive monitoring refers to estimating glucose levels without breaking the skin; in this work, it is achieved using a photoplethysmography (PPG) sensor (MAX30102). The proposed system integrates solar and piezoelectric energy harvesters regulated through a power management circuit to sustain continuous sensor operation. Blood glucose levels are estimated from PPG signals via machine learning, while harvested energy ensures device autonomy. A preliminary prototype demonstrates successful PPG acquisition, solar-powered operation, and energy harvesting simulations that align with estimated requirements. The key contributions of this work are: (1) hybrid solar–piezo energy harvesting for wearables, (2) integration of non-invasive PPG-based glucose monitoring, and (3) validation through prototype and simulation. This research highlights a self-powered, maintenance-free approach to wearable health monitoring.

***Index Terms*— CGM, Glucometer, Hybrid Energy Harvesting, PPG, Wearable**

I. INTRODUCTION

DIABETES mellitus is a global health concern affecting over 500 million people worldwide, with numbers steadily increasing. Effective management of this chronic condition requires frequent and reliable monitoring of blood glucose levels. Traditional finger-prick methods, while clinically reliable, are invasive, inconvenient, and unsuitable for continuous monitoring. Commercial continuous glucose monitors (CGMs) improve usability but rely on implantable sensors, require regular calibration, and depend on frequent battery charging, which limits long-term, maintenance-free use.

Non-invasive glucose monitoring provides a promising alternative by estimating blood glucose levels without penetrating the skin or drawing blood. Among available techniques, photoplethysmography (PPG) has gained attention for its ability to measure blood volume changes optically, offering a low-cost and wearable-compatible sensing approach. However, continuous operation of PPG sensors and associated data processing places high demands on battery capacity, making power autonomy a critical design challenge. To address these limitations, this research explores the development of a hybrid energy-powered wearable glucometer that combines non-invasive glucose monitoring with energy harvesting from ambient sources. The system utilizes a MAX30102 PPG sensor for signal acquisition, integrated with solar and piezoelectric harvesters for sustainable power generation regulated by a power management circuit. Preliminary results confirm that energy harvesting can sustain periodic operation, while prototype testing validates PPG acquisition and energy storage capability.

The main contributions of this work can be summarized as follows:

1. Development of a hybrid solar–piezo energy harvesting framework tailored for wearable devices.
2. Integration of non-invasive glucose monitoring using PPG sensors for trend estimation.
3. Design and prototyping of a wearable system demonstrating proof-of-concept feasibility.

This paper presents the system design, supporting simulations, prototype implementation, and preliminary results, while also outlining future directions including machine learning based glucose prediction, optimized PCB integration, and mobile application development.

A.G.M.M. Thilakarathne is an undergraduate from the Department of Electrical and Telecommunication Engineering, South Eastern University of Sri Lanka, Sri Lanka. (Email: malindamadhumal1999@gmail.com)

N.G.L.D. Madhumal is an undergraduate from the Department of Electrical and Telecommunication Engineering, South Eastern University of Sri Lanka, Sri Lanka.

S.K. Jaslin is a Lecturer at the Department of Electrical and Telecommunication Engineering, South Eastern University of Sri Lanka, Sri Lanka. (Email: jaslinshaleem@seu.ac.lk)

A.I.S. Juhaniya is a Senior Lecturer at the Department of Electrical and Telecommunication Engineering, South Eastern University of Sri Lanka, Sri Lanka. (Email: juhani90@seu.ac.lk)

ISSN: 2961-5992

II. Literature Review

The monitoring of blood glucose has evolved considerably, with approaches broadly classified as invasive, minimally invasive, and non-invasive methods. Parallel to this, advancements in energy harvesting technologies have supported the feasibility of autonomous wearable devices [1].

A. Invasive Methods

Invasive glucose monitoring, the most widely adopted approach, involves finger-prick blood sampling followed by chemical analysis using a glucometer. While clinically reliable, this method is painful, inconvenient, and unsuitable for continuous use [1].

B. Minimally Invasive Methods

Minimally invasive systems, such as commercial CGMs (e.g., Dexcom G6, FreeStyle Libre), employ subcutaneous sensors to measure interstitial glucose levels in real time [2,3]. These devices have improved patient adherence and glycemic control but still require skin penetration, calibration, and battery replacement, limiting their long-term usability. Continuous monitoring remains particularly critical for individuals with Type 1 diabetes [2] or gestational diabetes [4], who require timely glucose adjustments to prevent acute complications.

C. Non-Invasive Methods

Non-invasive glucose monitoring aims to estimate glucose concentration without breaking the skin. Among various techniques, photoplethysmography (PPG) has emerged as a promising candidate due to its simplicity, compatibility with wearables, and low cost [5,6]. PPG detects changes in blood volume optically, and while traditionally used for heart rate and oxygen saturation, research shows that glucose levels subtly affect vascular tone, viscosity, and microcirculation [6]. These physiological changes influence PPG waveform features such as peak intervals, amplitude, and spectral energy. By applying machine learning to such features, researchers have demonstrated reasonable accuracy for glucose trend estimation [7]. However, precision still lags behind invasive methods, leaving room for improvement [3].

D. Energy Harvesting for Wearables

The demand for autonomous wearables has driven research into sustainable energy harvesting. Piezoelectric harvesting converts biomechanical motion (e.g., walking, wrist movement) into electrical energy using materials such as PVDF or PZT, typically producing microwatt-to-milliwatt outputs [8,9]. Solar harvesting using thin-film photovoltaic cells provides a complementary source, delivering tens to hundreds of milliwatts under suitable lighting conditions [10]. Hybrid systems that integrate solar and piezoelectric elements improve energy availability across varied environments [11]. Other approaches, such as thermoelectric and RF harvesting, remain under investigation but are often limited by environmental constraints [12,13].

E. Research Gap

Despite advancements in both glucose sensing and energy harvesting, few studies have combined the two into a single, fully autonomous wearable system. Existing CGMs remain invasive or battery-dependent [14], while non-invasive proto types often lack sustainable power solutions [12]. This gap motivates the present work: the development of a hybrid powered wearable glucometer that leverages PPG-based noninvasive sensing for continuous glucose monitoring.

III. Methodology

The development of the hybrid energy-powered wearable glucometer was structured into five main stages: energy harvesting modeling, signal acquisition and preprocessing, machine learning–based glucose estimation, Android interfacing, and full system integration. The project is ongoing; therefore, completed and planned phases are distinguished clearly. Figure 1 illustrates the overall methodology.

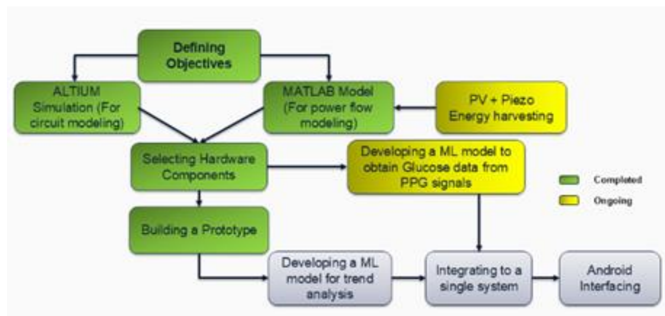

Fig. 1: Methodology Flow Chart

A. Energy Harvesting Simulation (Completed)

Energy harvesting simulations were carried out to evaluate system power autonomy. Component-level power consumption was modeled in MATLAB Simulink and Altium Designer. Key subsystems included the MAX30102 optical sensor, ESP32-C3 microcontroller with BLE communication, and the power regulation circuitry. Power consumption profiles were assessed for different modes (active, sleep, transmission), and solar and piezoelectric harvesting capacities were estimated using manufacturer data and simulations.

B. Signal Acquisition and Preprocessing (Ongoing)

The MAX30102 sensor (Figure 2) was used to collect red and infrared PPG signals. Preliminary acquisition confirmed reliable waveform capture. Planned preprocessing steps include digital noise filtering and feature extraction (e.g., amplitude, rise time, and frequency content), which will serve as inputs for glucose trend estimation models.

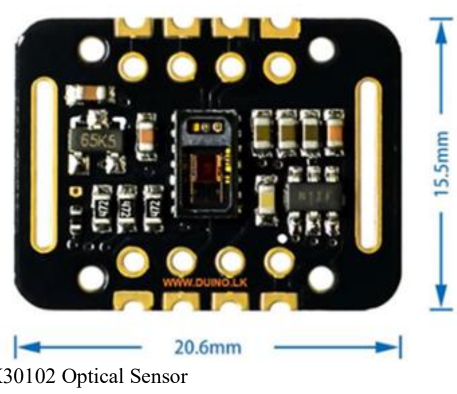

Fig. 2: MAX30102 Optical Sensor

ISSN: 2961-5992

C. Machine Learning for Glucose Estimation (Planned)

Glucose trend estimation will employ supervised regression models such as Random Forest, Support Vector Regression (SVR), or Gradient Boosting, trained on datasets of PPG features labeled with reference glucose values. Extracted features will include both time-domain and frequency-domain characteristics. Cross-validation will be applied to minimize overfitting and ensure subject-independent generalization. In a later stage, temporal models such as Long Short-Term Memory (LSTM) neural networks will be explored to forecast glucose trends. This phase is planned for future implementation once sufficient data are collected.

D. Android Interfacing (Planned)

A dedicated Android application will be developed to interface with the wearable via BLE. The app will provide real-time visualization of glucose trends, abnormal event alerts, battery status, and historical logging. Optional cloud synchronization will be considered for remote monitoring. This component is part of the next development phase.

E. System Integration (Planned)

A custom printed circuit board (PCB) will be designed to consolidate the optical sensor, microcontroller, power management unit, and energy harvesting modules into a compact wearable form factor. The system will then be housed in a 3D-printed enclosure for practical testing.

IV. Results and Discussion

At the current stage of development, only the energy harvesting simulations, preliminary prototyping, and basic PPG signal acquisition have been completed. Machine learning based glucose estimation, Android application interfacing, and full PCB integration remain as future work. The following results highlight validated components and discuss their implications.

A. Energy Harvesting Simulation

Solar and piezoelectric energy harvesting subsystems were modeled in MATLAB Simulink. Under standard test conditions, the solar panel (4 × 3 cm) produced 100–150 mW under direct sunlight and 10–50 mW under indoor lighting. These values align with reported performance of thin-film photovoltaics in similar wearable applications [10].

For piezoelectric harvesters, simulations modeled walking motion at ~1 Hz using standard ceramic disks. A single disk produced 1–3 mW, and an array of ten disks was estimated to generate ~30 mW. This is comparable to prior wearable piezoelectric harvesting studies [9], although efficiency strongly depends on motion intensity and mechanical coupling.

Together, the results confirm that while solar harvesting can provide the majority of energy under outdoor use, piezoelectric harvesters offer a complementary source for intermittent indoor or low-light conditions.

B. Energy Storage

A Li-ion battery (350 mAh, 3.7 V) was selected after initial consideration of supercapacitors. Simulations showed that charging solely from a 0.15 W solar panel requires approximately 10 hours, whereas a hybrid source could reduce charging time significantly. This finding is consistent with hybrid energy harvesting research emphasizing the importance of complementary sources for practical wearables [13].

C. Power Requirement Estimation

A preliminary power budget was calculated. The ESP32-C3 with BLE, MAX30102 sensor, OLED display, and regulation circuits together consumed ~1.4 W. With a 350 mAh Li-ion battery, this equates to ~55 minutes of continuous operation. While this is insufficient for real-world wearables, it provides a benchmark for optimization. Reducing OLED use, optimizing BLE duty cycles, and introducing low-power scheduling could extend operational lifetime substantially.

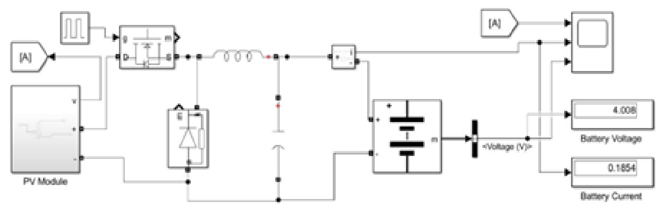

Fig. 3: Solar Energy Harvester Simulation in MATLAB

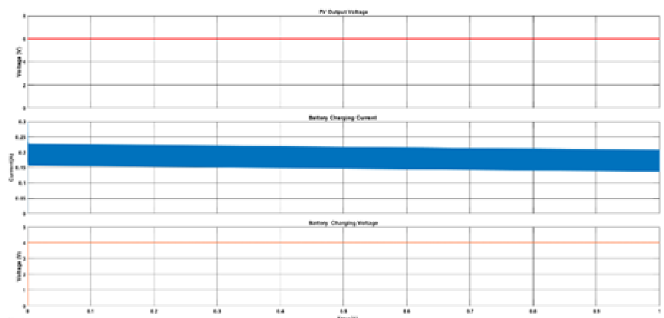

Fig. 4: Solar Energy Harvester Simulation Results

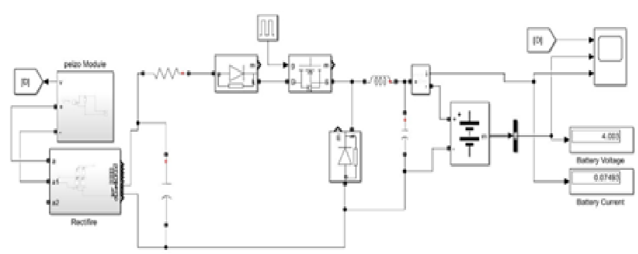

Fig. 5: Piezo Energy Harvester Simulation in MATLAB

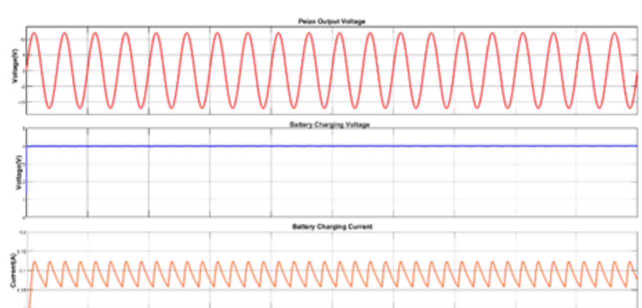

Fig. 6: Piezo Energy Harvester Simulation Results

ISSN: 2961-5992

TABLE I
POWER CONSUMPTION OF DEVICES

Device	V (V)	I (mA)	Power (mW)
ESP32 (+BLE)	6	150	900
MAX30102	5	12	60
SSD1306	5	30	150
MT3608	6	192	121
TP4056	3.3	311	173
Total			**1,404**

Solar Output Current:

$$I = \frac{0.15\,W}{3\,V} = 0.05\,A \quad (1)$$

Booster Output Voltage:

$$V = 4.2\,V \quad (2)$$

Charging Current:

$$I = \frac{0.15\,W}{4.2\,V} = 0.036\,A \quad (3)$$

Charging Time (100%):

$$t = \frac{350\,mAh}{35.71\,mA} = 9.8\,h \quad (4)$$

Maximum Load:

$$P_{load} = 1.404\,W \quad (5)$$

Battery Capacity:

$$E_{batt} = 350\,mAh \times 3.7\,V = 1.295\,Wh \quad (6)$$

Operation Time:

$$t = \frac{1.295\,Wh}{1.404\,W} = 0.922\,h = 55.34\,minutes \quad (7)$$

D. Circuit Validation and Prototype Assembly

Complete system including MCU, Optical Sensor, Voltage Booster, BMS, Battery and the Display was developed in the Altium Designer as a schematic (Figure 7).

A breadboard prototype was constructed (Figure 8). It successfully captured PPG signals through the MAX30102 sensor, processed them with the ESP32-C3 microcontroller, and displayed results (e.g., heart rate) on the OLED screen. The prototype operated for ~1 hour when charged solely using solar power.

However, the setup revealed important limitations:

Form factor: bulky and unsuitable for wearable integration. Power efficiency: high consumption from OLED and regulator circuits. Harvesting dependency: reliance on solar panels limits indoor usability. These limitations underscore the need for a custom PCB and improved energy scheduling.

E. PPG Signal Acquisition

Preliminary tests confirmed reliable acquisition of PPG signals. Figure 9 shows heart rate derived from processed signals. While glucose estimation was not implemented at this stage, the quality of captured PPG waveforms indicates feasibility for extracting glucose-related features in the next phase.

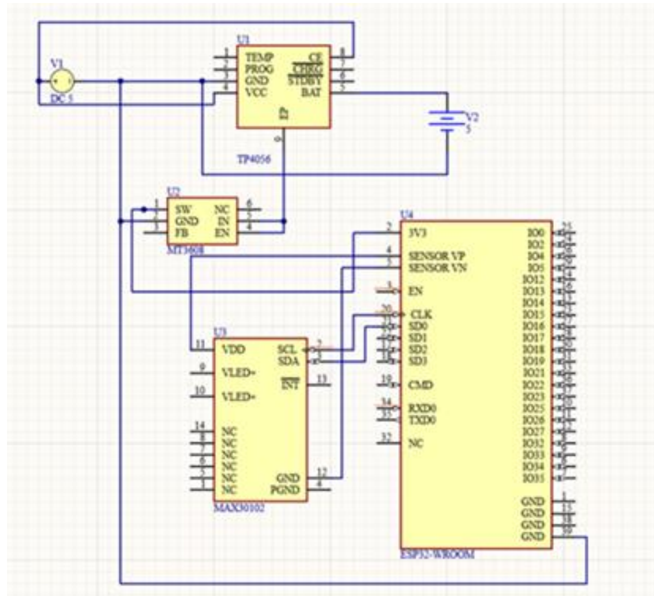

Fig. 7: Altium Schematic Diagram of the Circuit

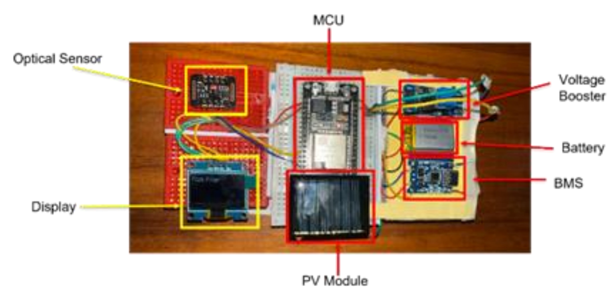

Fig. 8: Prototype Implementation

Fig. 9: Heart Rate Extraction from PPG

V. CONCLUSION

This work presents the ongoing development of a hybrid energy-powered wearable glucometer for non-invasive and continuous glucose monitoring. The system integrates a PPG sensor for optical signal acquisition with dual-source energy harvesting using solar and piezoelectric modules, regulated through a power management circuit. Simulation and prototype results confirm that harvested energy can sustain intermittent operation, and preliminary PPG acquisition validates the feasibility of non-invasive sensing. While current limitations

ISSN: 2961-5992

include high power demand, bulky form factor, and incomplete glucose estimation models, these findings demonstrate proof-of-concept viability. Future work will focus on implementing machine learning algorithms for glucose prediction, optimizing energy scheduling, and developing a custom PCB with compact integration to improve efficiency and wearability. Overall, this research highlights a promising pathway toward autonomous, maintenance-free wearable health monitoring systems.

REFERENCES

[1] G. Cappon, G. Acciaroli, M. Vettoretti, A. Facchinetti, and G. Sparacino, "Wearable Continuous Glucose Monitoring Sensors: A Revolution in Diabetes Treatment," *Electronics*, vol. 6, no. 3, p. 65, Sep. 2017, doi: https://doi.org/10.3390/electronics6030065.

[2] G. Cappon, M. Vettoretti, G. Sparacino, and A. Facchinetti, "Continuous Glucose Monitoring Sensors for Diabetes Management: a Review of Technologies and Applications," *Diabetes & Metabolism Journal*, vol. 43, no. 4, p. 383, 2019, doi: https://doi.org/10.4093/dmj.2019.0121.

[3] M. Mansour, M. Saeed Darweesh, and A. Soltan, "Wearable devices for glucose monitoring: A review of state-of-the-art technologies and emerging trends," *Alexandria Engineering Journal*, vol. 89, pp. 224–243, Feb. 2024, doi: https://doi.org/10.1016/j.aej.2024.01.021.

[4] C.-W. Tsai, C.-H. Li, R. W.-K. Lam, C.-K. Li, and S. Ho, "Diabetes Care in Motion: Blood Glucose Estimation Using Wearable Devices," *IEEE Consumer Electronics Magazine*, vol. 9, no. 1, pp. 30–34, Jan. 2020, doi: https://doi.org/10.1109/mce.2019.2941461.

[5] J. Li, Tobore Igbe, Y. Liu, Abhishek Kandwal, and L. Wang, "Non-invasive Monitoring of Three Glucose Ranges Based On ECG By Using DBSCAN-CNN," *IEEE Journal of Biomedical and Health Informatics*, vol. 25, no. 9, pp. 3340–3350, Sep. 2021, doi: https://doi.org/10.1109/jbhi.2021.3072628.

[6] S. Vanaja *et al.*, "Non-invasive glucometer monitoring system through optical based near-infrared sensor method," *Computer methods in biomechanics and biomedical engineering. Imaging & visualization*, vol. 12, no. 1, Apr. 2024, doi: https://doi.org/10.1080/21681163.2024.2327423.

[7] Touria El Idriss, A. Idri, Ibtissam Abnane, and Zohra Bakkoury, "Predicting blood glucose using an LSTM Neural Network," *Computer Science and Information Systems (FedCSIS), 2019 Federated Conference on*, Sep. 2019, doi: https://doi.org/10.15439/2019f159.

[8] S. Afridi and A. Basit, "Design of Hybrid Power System using PV and Piezoelectric Energy Harvester," *International journal of Engineering Works*, vol. 10, no. 03, pp. 16–21, Mar. 2023, doi: https://doi.org/10.34259/ijew.23.10031621.

[9] "Piezoelectric-driven Charging Supercapacitors for Biomedical Sensor Applications | Journal of Environmental Nanotechnology," *Nanoient.org*, 2019. https://nanoient.org/journals/index.php/jent/article/view/801.

[10] A. S. Khan and F. U. Khan, "A Wearable Solar Energy Harvesting Based Jacket With Maximum Power Point Tracking for Vital Health Monitoring Systems," *IEEE Access*, vol. 10, pp. 119475–119495, 2022, doi: https://doi.org/10.1109/access.2022.3220900.

[11] A. K. Ali, A. A. Abdulrazzaq, and A. H. Mohsin, "A Dynamic Simulation of a Piezoelectric Energy-Harvesting System Integrated with a Closed-Loop Voltage Source Converter for Sustainable Power Generation," *Processes*, vol. 12, no. 10, pp. 2198–2198, Oct. 2024, doi: https://doi.org/10.3390/pr12102198.

[12] S. Banerjee and G. Slaughter, "Flexible battery-less wireless glucose monitoring system," *Scientific Reports*, vol. 12, no. 1, Jul. 2022, doi: https://doi.org/10.1038/s41598-022-16714-1.

[13] "Piezoelectric-driven Charging Supercapacitors for Biomedical Sensor Applications | Journal of Environmental Nanotechnology," *Nanoient.org*, 2019. https://nanoient.org/journals/index.php/jent/article/view/801.

[14] Q. Chen, Y. Zhao, and Y. Liu, "Current development in wearable glucose meters," *Chinese Chemical Letters*, May 2021, doi: https://doi.org/10.1016/j.cclet.2021.05.043.

ISSN: 2961-5992