Task-3: Non-Invasive CGM Monitoring

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Team members:
1- Ahmed Adil
2- Ammar Yaseer
3- Mostafa Mousa
4- Ziad Wael
5- Hussein Mohammed

1. Introduction

Diabetes management currently relies significantly on invasive glucose monitoring techniques such as fingersticks or subcutaneous sensors. These methods can cause discomfort, skin irritation, and involve recurring costs. This project addresses the need for more user-friendly monitoring solutions by developing a functional hardware prototype of a non-invasive Continuous Glucose Monitoring (CGM) system. The aim is to explore a physiological approach to estimate blood glucose levels without skin penetration, meeting the growing demand for comfortable and user-friendly diabetic monitoring solutions.

2. Objective

To design and implement a functional non-invasive CGM hardware prototype utilizing an optical sensing method. The prototype must integrate at least one novel feature designed to enhance the system's potential accuracy, usability, or clinical value.

3. Background

With a rising global prevalence of diabetes (affecting over 537 million adults), the demand for convenient and continuous monitoring systems is increasing.
Non-invasive methods offer potential advantages over traditional techniques, including:

- Elimination of needle-associated pain and infection risk.
- Potential for continuous, real-time monitoring without implanted components.
- Reduction in waste and long-term costs associated with disposable sensors/strips.

4. Methodology

4.1 Physiological Approach: Near-Infrared (NIR) Transmission Spectroscopy

The core sensing mechanism selected for this prototype is Near-Infrared (NIR) spectroscopy, utilizing light transmission through the fingertip. This approach is based on the principle that glucose, along with other constituents of biological tissue (like water and blood), absorbs NIR light. By measuring the attenuation of 940nm NIR light passing through the tissue, variations related to changes in tissue composition, potentially including glucose concentration, can be detected.

4.2 Hardware Components

The functional hardware prototype was constructed using the following components:

- **Microcontroller:** Arduino Uno R3 (Controls system timing, data acquisition, processing, and output).
- **NIR Light Source:** 1x 940nm Infrared LED (5mm, Through-Hole).
- **Light Detector:** 1x BPW34 Silicon PIN Photodiode (Detects transmitted NIR light intensity).
- **Signal Conditioning:** 1x LM358 Dual Op-Amp (Configured as a Transimpedance Amplifier (TIA) with a 1MΩ feedback resistor - adjustable - to convert photodiode current to voltage).
- **Temperature Sensor (Novel Feature):** 1x DS18B20 Digital Temperature Sensor (TO-92 package).
- **Passive Components:** Resistors (220Ω for LED, 4.7kΩ pull-up for DS18B20, 1MΩ for TIA feedback), Capacitors (0.1µF for decoupling).
- **Interface:** Solderless Breadboard, Jumper Wires, Plastic Clothes Peg (modified to hold sensors against the fingertip and block ambient light).
- **Power:** USB connection to PC.

4.3 Signal Processing and Glucose Level Estimation

1. **Optical Signal Acquisition:** The Arduino pulses the 940nm LED on. The photodiode detects the transmitted light, and the TIA circuit amplifies the signal. The Arduino ADC reads the resulting voltage.
2. **Noise Filtering:** A moving average filter (averaging the last 50 raw optical readings) is implemented in the Arduino software to smooth rapid fluctuations (e.g., PPG signal, noise), yielding a more stable averageOptical signal.
3. **Temperature Measurement:** The DS18B20 sensor is read concurrently to obtain the skin temperature (temperatureC).
4. **Glucose Level Mapping:** The processed averageOptical signal is converted into an estimated glucose level (mg/dL). This conversion employs a linear mapping function based on defined correspondence points between expected operational

optical signal levels (optical_low_assumed, optical_high_assumed) and a target physiological glucose range (glucose_low_mgdl, glucose_high_mgdl). A minor adjustment based on the measured temperature (temperatureC) relative to a baseline (baseline_temp_C) is also incorporated into the calculation. The final output is constrained to a plausible physiological range (40-400 mg/dL). *(Note: The specific optical range values require adjustment based on observed prototype readings)*.

5. **Output:** The system outputs the timestamp, averaged optical reading, raw optical reading, measured temperature, and the calculated estimated glucose level (mg/dL) to the Serial Monitor.

5. Novel Feature: Integrated Skin Temperature Monitoring

To address the known challenge of skin variability affecting non-invasive optical measurements, a DS18B20 digital temperature sensor was integrated into the fingertip sensor assembly.

- **Rationale:** Skin temperature influences local blood flow, tissue optical properties, and optoelectronic component performance. Measuring temperature provides critical contextual data for interpreting the optical signal.
- **Implementation:** The sensor is positioned in contact with the skin near the optical site and read simultaneously with the optical sensor.
- **Impact:** This feature enhances the system by quantifying a key variable impacting optical readings. The temperature data is actively incorporated into the glucose level calculation, demonstrating a mechanism for thermal compensation. Monitoring temperature allows for better interpretation of optical signal fluctuations and represents a necessary step towards improving measurement reliability in non-invasive systems.

6. Results

The prototype successfully acquired optical signals via NIR transmission through the fingertip and measured skin temperature concurrently. The moving average filter effectively stabilized the optical signal compared to raw readings. The system continuously outputted all measured and calculated parameters, including the estimated glucose level, to the Serial Monitor. Testing confirmed that the optical signal responded to the presence of the finger and that the temperature sensor provided real-time skin temperature readings. Variations in the optical signal were observed to correlate with changes in measured skin temperature, demonstrating the relevance of the integrated novel feature. The mapped glucose level output varied in response to changes in the input optical and temperature signals according to the implemented

mapping function.

7. Usability and Clinical Value

The prototype demonstrates the feasibility of constructing a low-cost, non-invasive optical sensing system using readily available components. The modified clothes peg provides a simple fingertip interface. The integration of temperature sensing addresses a known limitation of optical methods, adding potential clinical value by providing data essential for developing more robust calibration models needed for accurate glucose estimation. While this prototype requires significant further development and clinical validation for medical use, it serves as a functional proof-of-concept for needle-free physiological monitoring.

8. Conclusion

This project resulted in the successful development of a functional hardware prototype for non-invasive physiological monitoring based on NIR spectroscopy. The system effectively measures light attenuation through the fingertip and integrates a novel temperature sensing feature, providing essential context for the optical readings. The prototype outputs processed sensor data, including a mapped glucose level estimate derived from the optical and thermal signals, demonstrating the core principles of the chosen approach and the integrated feature. This work highlights the potential of non-invasive monitoring while underscoring the importance of addressing confounding variables like temperature to advance towards reliable clinical application.