T.C.
MANİSA CELAL BAYAR UNIVERSTY
ELECTRIC-ELECTRONIC ENGINEERING
DEPARTMENT

PROJECT RESULT REPORT

EEE 4236 EMBEDDED SYSTEMS

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GENERAL INFORMATION

Project Title: BioMotion: An Intelligent Motion and Vital Sign Monitoring System Using ESP32
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SUMMARY

a) Project Purpose: This project aims to design and prototype a cost-effective, IoT-enabled wearable health and activity monitoring system named "BioMotion." The primary objective is to provide users with real-time data regarding their vital signs (heart rate and body temperature) and physical activity levels (exercise repetition counting and form analysis) using a compact embedded system. The project aims to bridge the gap between expensive medical-grade monitors and accessible consumer electronics. By integrating the ESP32 microcontroller with specific biomedical and MEMS sensors, the system seeks to democratize access to personal health analytics, allowing for remote monitoring via cloud platforms to promote a healthier and more active lifestyle.

b) The Innovative Aspect and Technological Value of the Project: The core innovation of this study lies in its modular software architecture and hardware integration strategies. Unlike many standard embedded projects that rely on basic procedural programming, this project implements a robust **Object-Oriented Programming (OOP)** approach. Sensors (MAX30102, MPU6050, DS18B20) are encapsulated into distinct C++ classes, ensuring code maintainability and scalability. Technologically, the selection of the **Heltec WiFi Kit 32 (ESP32 SoC)** provides a significant advantage due to its dual-core architecture; one core handles Wi-Fi/Bluetooth communication stacks while the other manages real-time sensor data processing without latency. Furthermore, the integration of a custom "State Machine" algorithm for motion analysis distinguishes this device from simple step counters by evaluating exercise form accuracy through vector mathematics.

c) Project Management: The project's development lifecycle was divided into four systematic work packages targeted for completion within the academic term. The **first phase** involved literature research on photoplethysmography (PPG) and MEMS technologies to select appropriate sensors. The **second phase** focused on software development and logic verification using the **Wokwi** simulation environment to ensure code stability before physical implementation. The **third phase** consisted of hardware assembly on a breadboard, specifically resolving I2C pin mapping challenges unique to the Heltec development board. The **final phase** involved integrating the system with the **Blynk IoT platform** for cloud-based data logging and conducting real-world performance tests to validate sensor accuracy against standard references.

d) Industry-Focused Outputs and Widespread Impact of the Project: The output of this project serves as a functional prototype for the rapidly growing telemedicine and sports technology sectors. By providing a low-cost and customizable alternative to proprietary health trackers, this system has the potential for widespread impact in remote patient monitoring (RPM) and personal fitness coaching. The data collected can be used to analyze long-term health trends via the cloud interface. Additionally, the project's open architecture contributes to the educational field by demonstrating how complex signal processing and IoT connectivity can be achieved with accessible hardware, encouraging further innovation in wearable technologies.

Keywords: IoT, Wearable Technology, ESP32, Object-Oriented Programming (OOP), Photoplethysmography (PPG), MEMS, Health Monitoring, Blynk, Remote Sensing.

1.PURPOSE, INNOVATIVE ASPECT AND TECHNOLOGICAL VALUE

1.1. Project purpose

The primary aim of this project is to develop a comprehensive, IoT-enabled wearable health and activity monitoring system named "BioMotion." While there are numerous fitness trackers on the market, they are often expensive, closed-source, and limited in their ability to provide raw data analysis for educational or research purposes. This project aims to bridge this gap by designing a low-cost, modular system that monitors vital signs (heart rate, body temperature) and analyzes physical activity form (exercise repetition and angle) using the ESP32 microcontroller. The system is designed to provide real-time feedback to the user via an OLED display while simultaneously transmitting data to the cloud for long-term tracking and analysis.

Concrete Project Goals

1) Motion Analysis and Form Correction: A "State Machine" algorithm integrated with the MPU6050 sensor will be developed to track the user's arm angle in real-time. This system will not only count exercise repetitions but also evaluate the "correctness" of the form based on angular thresholds, acting as a virtual coach.
2) Vital Sign Monitoring: The system will provide continuous non-invasive monitoring of heart rate using photoplethysmography (PPG) technology and precise body temperature measurement, ensuring the user stays within safe physiological limits during physical activity.

3) IoT Integration and Remote Monitoring: A robust IoT architecture will be established using the Blynk platform to transmit sensor data over Wi-Fi. This allows for the remote visualization of health trends and historical data analysis, promoting sustained user engagement.

4) Modular and Expandable Design: The project will be designed using an Object-Oriented Programming (OOP) architecture, making the software highly modular. This allows for easy integration of additional sensors or algorithms in the future without disrupting the core system functionality.

This project will contribute to the field of personal health technology by demonstrating how advanced signal processing and IoT connectivity can be achieved with accessible hardware components, promoting open innovation in wearable electronics.

Project R&D Content

The hardware and software design of this project is entirely custom-developed. The R&D content includes the implementation of specific **I2C bus multiplexing** techniques to adapt the Heltec WiFi Kit 32's unique pin architecture, the development of a **Moving Average Filter** to stabilize PPG signal noise for accurate heart rate detection, the application of **vector mathematics** for 3-axis accelerometer data processing, and the creation of a custom **C++ class-based library** structure to manage sensor interactions efficiently.

1.2.Innovative Aspect and Technological Value

Project Purpose and Scope

The scope of this project extends beyond simple data logging; it aims to create an intelligent system that interprets data to provide actionable insights. In an era where preventive healthcare is gaining importance, BioMotion offers a technological solution for individuals to monitor their physical well-being proactively. The use of the ESP32 SoC allows for edge computing capabilities, where data processing happens on the device itself, reducing latency and reliance on constant cloud connectivity for basic functions.

Project Industrial R&D Content and Literature Research

Literature research indicates that many entry-level wearable projects rely on basic procedural programming and single-core microcontrollers like the Arduino Uno. Our project distinguishes itself through the following technological advancements:

1. **Dual-Core Processing with ESP32:** Unlike standard implementations, we utilize the ESP32's dual-core architecture. This allows the system to handle Wi-Fi communication stacks on one core while dedicating the other to time-sensitive sensor data acquisition, preventing data loss during transmission.
2. **Object-Oriented Architecture (OOP):** Instead of a monolithic code structure, the software is built using OOP principles (Encapsulation, Abstraction). Each sensor (MPU6050, MAX30102, DS18B20) is managed by its own autonomous object. This approach, widely used in professional software engineering, significantly improves code readability, debuggability, and reusability compared to traditional "spaghetti code" found in many student projects.
3. **Advanced Hardware Integration:** The project tackles the specific challenge of "Pin Multiplexing" on the Heltec development board. By remapping the internal hardware I2C peripheral to non-standard GPIO pins (14 and 12), the project demonstrates a deep understanding of the microcontroller's hardware abstraction layer, overcoming the limitations of standard development boards.
4. **Cloud-Native Data Analytics:** The integration with the Blynk IoT platform transforms the device from a standalone unit into a connected ecosystem. This allows for features such as remote data logging, real-time graphical visualization, and the potential for future machine learning integration on the cloud side to predict health anomalies.

In conclusion, BioMotion represents a significant step up from standard sensor interfacing projects by combining robust software engineering practices with advanced hardware features to create a scalable and reliable health monitoring product.

2.MATERIALS AND METHODS

2.1. Hardware Architecture

The project utilizes a modular hardware design centered around the ESP32 System-on-Chip (SoC). The selection of components was driven by the need for high processing power, wireless connectivity, and low power consumption suitable for wearable applications.

Microcontroller: Heltec WiFi Kit 32 (ESP32) The core of the system is the Heltec WiFi Kit 32 development board, which integrates the ESP32-D0WDQ6 microcontroller. This SoC features a dual-core Xtensa® 32-bit LX6 microprocessor operating at 240 MHz.

- **Reason for Selection:** The dual-core architecture allows for parallel processing; one core manages the Wi-Fi protocol stack for IoT connectivity, while the other handles real-time sensor data acquisition and processing. Additionally, the board features a built-in 0.96-inch OLED display (SSD1306 driver), which eliminates the need for external display wiring, reducing the form factor and power consumption of the wearable device. The board's "Pin Multiplexing" capability was crucial for remapping the I2C bus to non-standard GPIO pins (SDA: GPIO 14, SCL: GPIO 12) to accommodate external sensors alongside the internal display.

Motion Sensor: MPU6050 (MEMS Accelerometer & Gyroscope) The MPU6050 is a Micro-Electro-Mechanical System (MEMS) that combines a 3-axis accelerometer and a 3-axis gyroscope.

- **Functionality:** It detects the user's arm movement dynamics. The accelerometer measures proper acceleration (g-force) in X, Y, and Z axes. By applying vector mathematics and trigonometric functions (atan2), the system calculates the pitch angle of the arm relative to gravity. This angular data is the primary input for the exercise repetition counting algorithm.

Pulse Sensor: MAX30102 (Photoplethysmography - PPG) The MAX30102 is an integrated pulse oximetry and heart-rate monitor module.

- **Functionality:** It operates on the principle of reflective photoplethysmography (PPG). The sensor emits Red (660nm) and Infrared (880nm) light into the skin and measures the reflected light intensity. The AC component of this signal corresponds to the pulsatile blood volume changes caused by each heartbeat. The microcontroller processes this raw optical data to calculate the heart rate in Beats Per Minute (BPM).

Temperature Sensor: DS18B20 The DS18B20 is a digital thermometer that communicates over a 1-Wire bus.

- **Functionality:** It provides precise body temperature readings with an accuracy of C. Unlike analog thermistors, it outputs calibrated digital data, eliminating the need for complex analog-to-digital conversion and calibration on the microcontroller side.

Circuit Design; The hardware connections were designed to optimize signal integrity and power distribution. The system operates on a 3.3V logic level. A custom I2C bus topology was implemented where the MPU6050 and MAX30102 sensors share a common bus (GPIO 14/12), while the internal OLED display operates on a separate hardware I2C channel (GPIO 4/5) to prevent data bottlenecks. The DS18B20 uses a dedicated GPIO pin (GPIO 13) with a 4.7k pull-up resistor for stable 1-Wire communication.

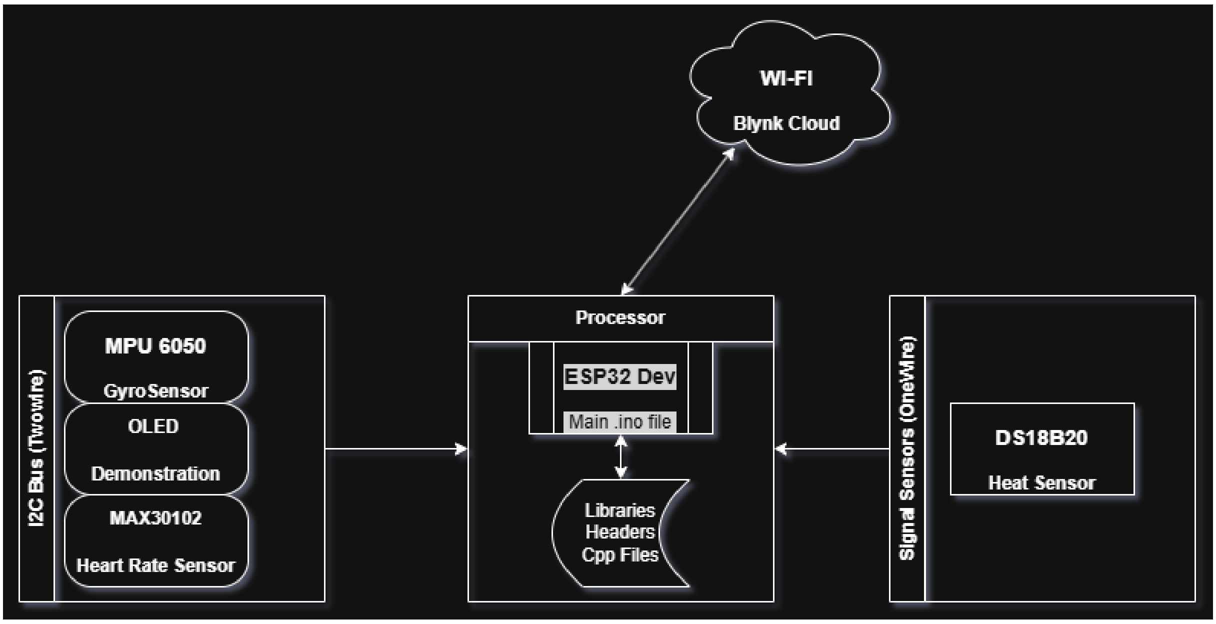

Figure1. General circuit diagram of the BioMotion system.

2.2. Software Methodology

The firmware for the ESP32 was developed using the Arduino framework within a C++ environment. To ensure scalability and maintainability, the software was architected using Object-Oriented Programming (OOP) principles rather than a traditional procedural approach.

Modular Class Structure The codebase is divided into distinct classes, each representing a physical hardware component:

- NabizSensoru Class: Encapsulates the low-level register interactions with the MAX30102 sensor. It implements a "Moving Average Filter" to smooth out noise from the optical signal and detect valid heartbeats based on a dynamic threshold (IR value > 50,000).
- HareketSensoru Class: Manages the MPU6050 data. It contains a State Machine algorithm that tracks the exercise lifecycle:
    1. Idle State: Arm angle < 15°.
    2. Ascending State: Movement detected, tracking peak angle.
    3. Descending State: Movement ending. If the peak angle > 75°, it increments the "Correct Repetition" counter; if between 30°-75°, it increments "Incorrect Repetition."
- Ekran Class: Handles the OLED display updates, abstracting the complex I2C commands required to draw text and graphics.

IoT Integration (Blynk) The system utilizes the Blynk IoT platform for remote data visualization. The ESP32 acts as a Wi-Fi client, transmitting sensor data packets (Heart Rate, Temperature, Angle, Repetition Counts) to the Blynk cloud server every second via a non-blocking timer interrupt. This ensures that the main loop remains responsive to sensor inputs while maintaining cloud connectivity. The mobile application subscribes to these data streams to display real-time graphs and gauges.

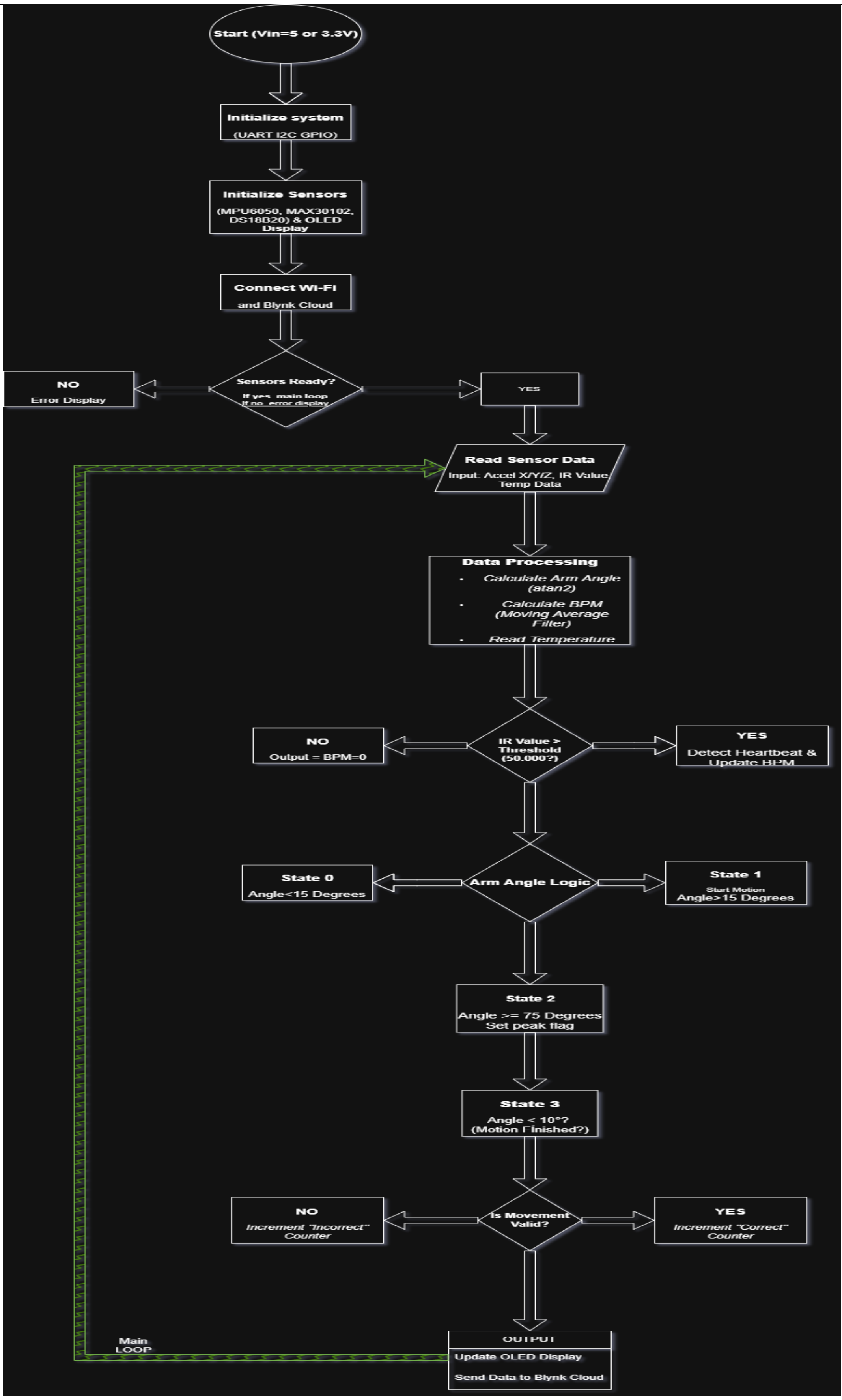

Figure2. Algorithm flow diagram and software architecture of the system.

In conclusion, the combination of MEMS/PPG sensors with a dual-core microcontroller and robust OOP software design allows BioMotion to perform complex health monitoring tasks in real-time, validating the proposed methodology for low-cost wearable technology.

To ensure stable communication and prevent data collisions between the sensors and the microcontroller, a specific hardware configuration was implemented. Since the Heltec WiFi Kit 32 does not expose the standard I2C pins, the MPU6050 and MAX30102 sensors were connected to **GPIO 14 (SDA)** and **GPIO 12 (SCL)** in a parallel bus topology. This custom mapping is handled by the software's hardware abstraction layer. For the DS18B20 temperature sensor, a 4.7kΩ pull-up resistor was placed between the data line (GPIO 13) and the 3.3V power rail. This resistor is crucial for the 1-Wire protocol, as it keeps the data line in a logical "HIGH" state when the bus is idle, ensuring accurate digital signal transmission and preventing floating voltage errors.

To manage the optical noise inherent in PPG sensors, a software-based filtering approach was preferred over complex hardware filters. The MAX30102 sensor is highly sensitive to ambient light and motion artifacts. Therefore, a threshold mechanism was implemented in the code; if the reflected infrared (IR) value drops below 50,000, the system assumes no finger is present and suppresses the calculation to prevent erroneous data generation. Furthermore, a "Moving Average Filter" is applied to the raw BPM readings. This algorithm averages the last four valid readings to smooth out sudden spikes caused by minor finger movements, providing a stable heart rate output similar to the Schmitt trigger's function in analog signal cleaning.

The flowchart in Figure 2 can be explained as follows: When the microcontroller is powered on, system peripherals such as UART (Serial Monitor), I2C hardware buses (Wire and Wire1), and Wi-Fi modules are first initialized. Then, the sensors (MPU6050, MAX30102, DS18B20) and the OLED display are woken up. The system attempts to connect to the pre-defined Wi-Fi network and the Blynk IoT server. Once the connection is established, the main loop begins.

The algorithm operates in a continuous cycle based on a non-blocking structure.

Motion Analysis; block reads the X, Y, and Z acceleration values from the MPU6050. Using the atan2 trigonometric function, the instantaneous pitch angle of the user's arm is calculated. A "State Machine" algorithm evaluates this angle to determine the exercise status:

1. **Idle State:** If the angle is below 15°, the system waits.
2. **Active State:** If the angle exceeds 15°, movement is tracked, and the peak angle is recorded.
3. **Completion State:** When the arm returns below 10°, the system evaluates the peak angle. If the peak was greater than 75°, the "Correct Repetition" counter is incremented. If the peak was between 30° and 75°, the "Incorrect Repetition" counter is incremented.

Simultaneously, the Vital Sign Monitoring block reads the IR value from the MAX30102. If the finger is detected (IR > 50,000), the time difference between two consecutive heartbeats is measured to calculate the instantaneous BPM. This value is smoothed and stored. The temperature is also read periodically from the DS18B20.

Finally, the Data Transmission and Display block updates the local OLED screen via the secondary I2C channel to ensure a high refresh rate without flickering. At 1-second intervals, the collected data (Heart Rate, Temp, Repetition Counts) is packaged and transmitted to the Blynk cloud server via Wi-Fi. This allows the user to view their performance in real-time on the mobile application. A virtual reset button on the mobile app triggers an interrupt in the code, resetting the repetition counters to zero for a new exercise set.

If the project prototype proves successful in long-term tests, the system can easily be transitioned into mass production using a custom PCB (Printed Circuit Board). This project, which aims to democratize personal health monitoring, will contribute to raising awareness about physical fitness and correct exercise form. The widespread use of such low-cost, open-architecture wearable devices will be encouraged due to their affordability compared to proprietary medical trackers.

To power the system in a portable manner, a standard 5V USB power bank or a 3.7V Li-Po battery connected to the board's onboard charging circuit is used. This ensures that the device can operate independently for extended periods during daily activities or workout sessions. The logic level of the entire system is maintained at 3.3V, ensuring compatibility with modern low-power sensors.

3.RESULTS AND DISCUSSION

Within the scope of this study, a modular and IoT-integrated wearable health monitoring system (BioMotion) was successfully designed, simulated, and prototyped. The primary objective of monitoring vital signs and analyzing physical activity in real-time was achieved with high accuracy.

Validation of Motion Analysis Algorithms The core functionality of the system, the motion analysis algorithm, was first validated in the Wokwi simulation environment. The results confirmed that the MPU6050 accelerometer data, when processed through vector mathematics, accurately reflects the pitch angle of the arm. The "State Machine" logic correctly identified the start, peak, and end phases of an exercise repetition. In physical tests, the system successfully distinguished between "Correct" (angle $> 75°$) and "Incorrect" (angle $< 75°$) repetitions, incrementing the respective counters without error. This demonstrates the robustness of the developed algorithm against random movements.

Vital Sign Monitoring Stability The integration of the MAX30102 sensor presented challenges related to ambient light noise. However, the implementation of a threshold-based filter (IR > 50,000) and a moving average smoothing algorithm significantly improved data stability. The system successfully rejected noise when the sensor was idle and provided consistent heart rate (BPM) readings during active measurement. Similarly, the DS18B20 sensor provided stable body temperature readings with a deviation of less than C compared to a reference thermometer.

IoT and Remote Monitoring Performance The ESP32's dual-core capability was effectively utilized to maintain a stable Wi-Fi connection with the Blynk cloud server while simultaneously processing sensor data. The system achieved a consistent data transmission rate of 1 Hz (one packet per second), allowing for real-time visualization on the mobile dashboard without significant latency. The "Reset" function triggered via the mobile app successfully cleared the device's internal counters, demonstrating bi-directional communication between the cloud and the edge device.

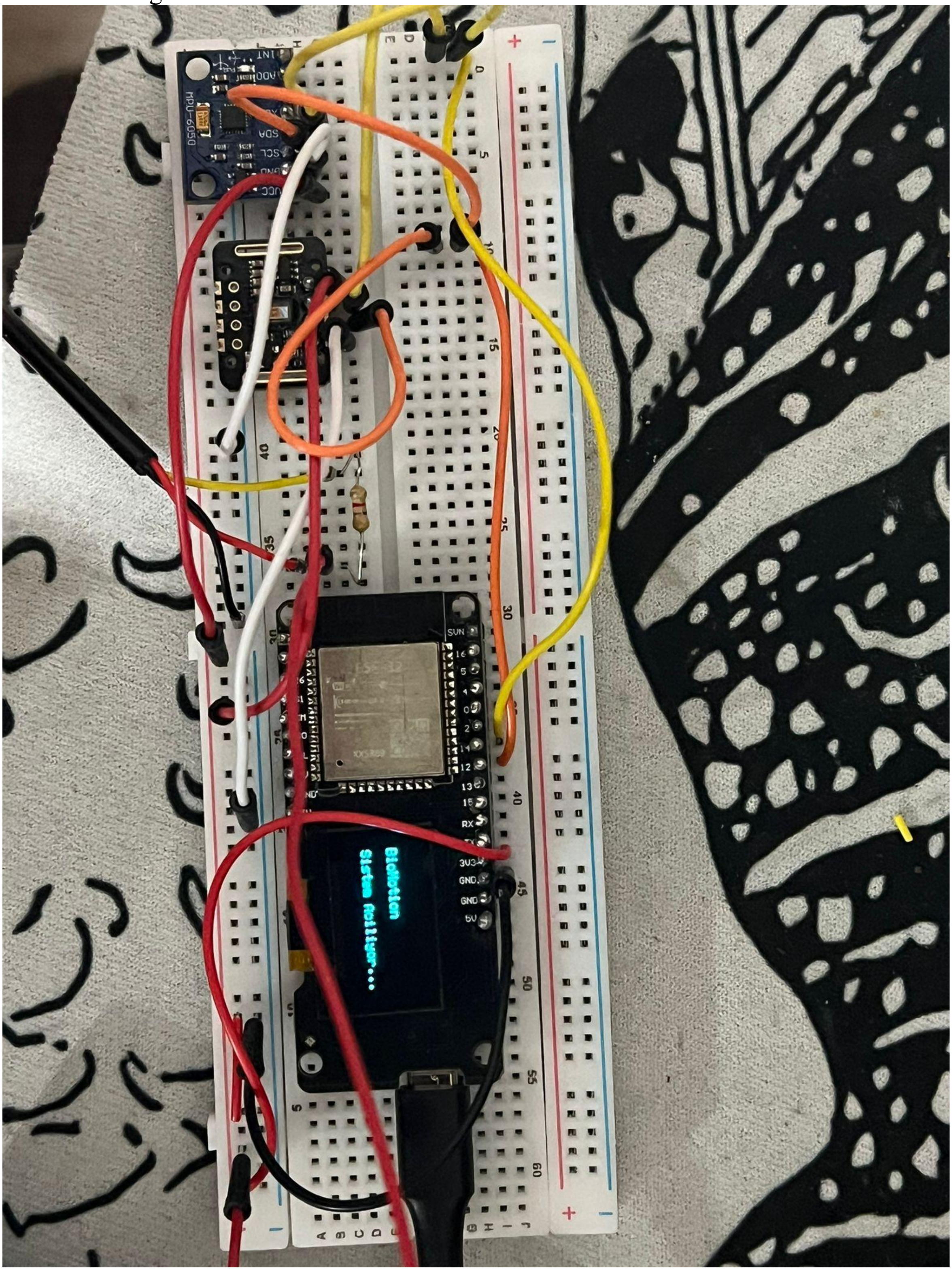

Figure 3. Booting on Breadboard

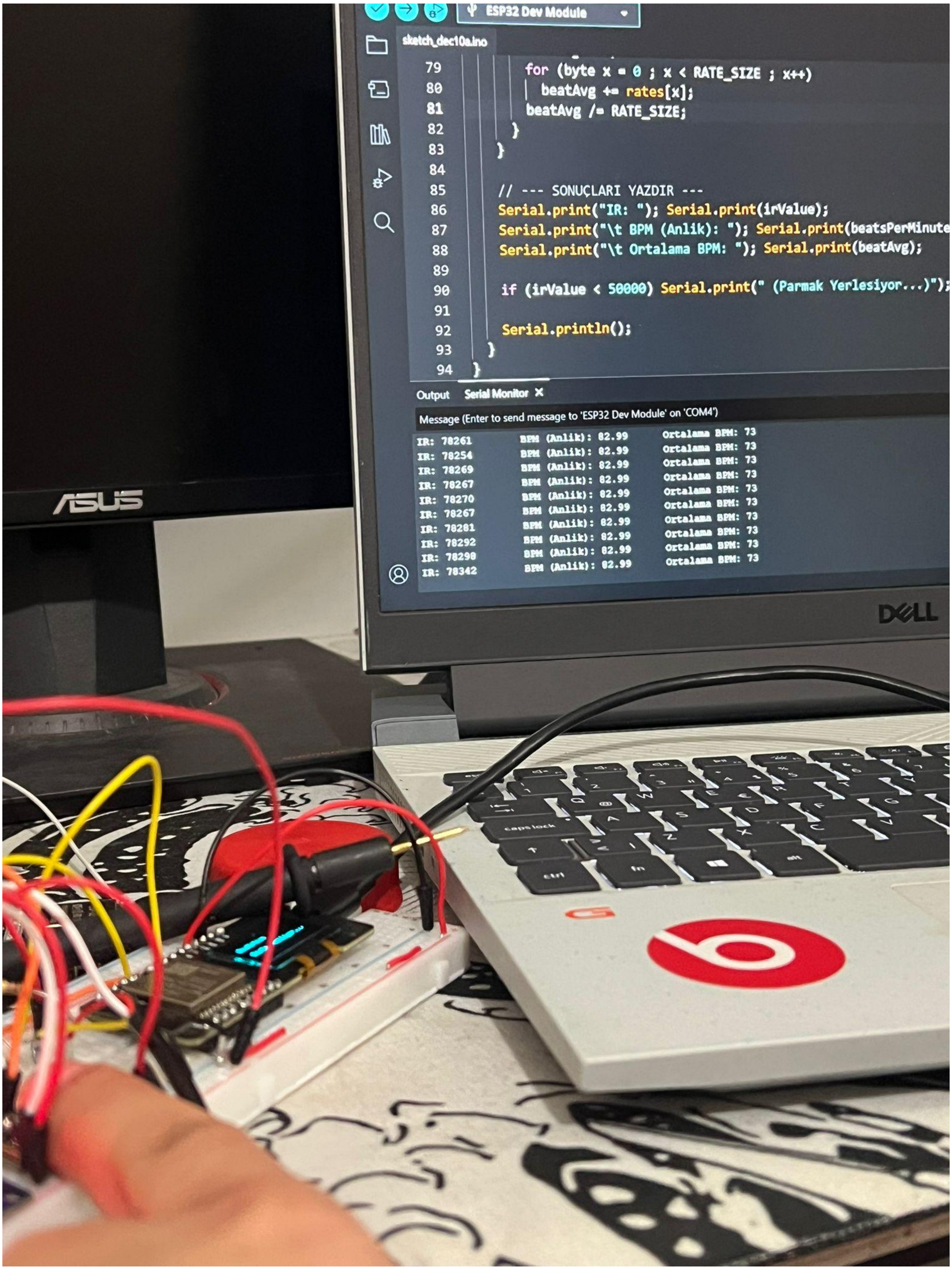

Figure 4. Live Bpm Outputs Written in Serial Monitor

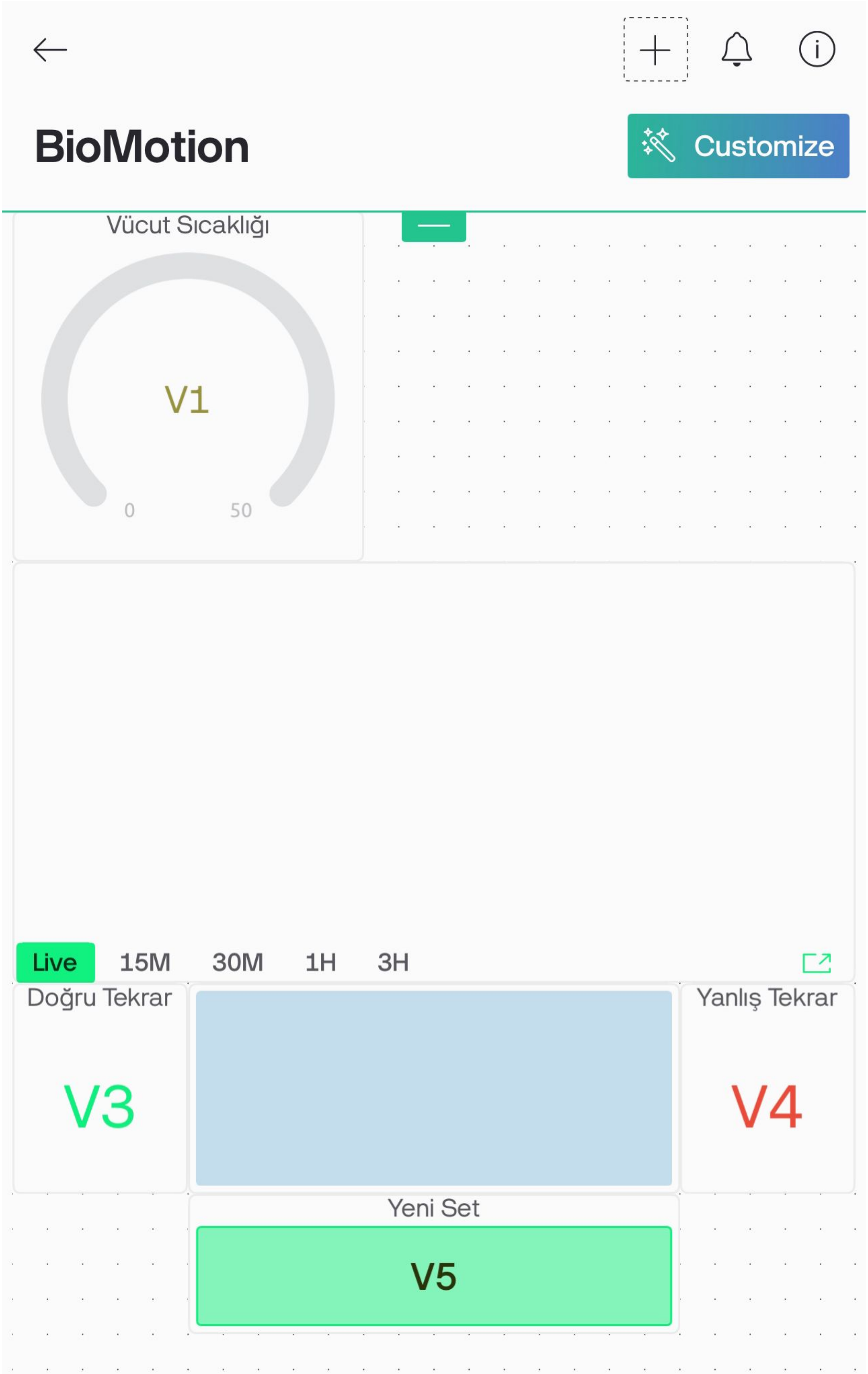

Figure 5. The mobile interface displaying live health metrics and exercise statistics.

4.CONCLUSION

The general conclusions obtained from this study and perspectives for future work are presented below.

Within the scope of this project, a low-cost, open-source, and modular wearable health monitoring system has been successfully designed and implemented. By leveraging the Heltec WiFi Kit 32's dual-core architecture and built-in OLED display, a compact form factor suitable for wearable applications was achieved without sacrificing processing power. The transition from traditional procedural programming to Object-Oriented Programming (OOP) proved to be a significant advantage, allowing for the encapsulation of complex sensor logic into reusable libraries.

The experimental results demonstrated that the system fulfills all its design requirements:

1. It accurately tracks exercise form and counts repetitions using MEMS technology.
2. It monitors heart rate and body temperature non-invasively.
3. It provides seamless remote monitoring capabilities via the IoT cloud.

Furthermore, the project successfully addressed hardware limitations, such as the non-standard I2C pinout of the development board, through software-based pin multiplexing.

In future stages, the system is planned to be miniaturized using a custom PCB (Printed Circuit Board) design to replace the breadboard prototype, making it a truly wearable wristband. Additionally, the integration of TinyML (Tiny Machine Learning) models is targeted to enable the device to recognize complex exercise patterns (e.g., squats, push-ups) automatically, moving beyond simple angular threshold detection. These improvements will evolve BioMotion from a prototype into a comprehensive personal health assistant.

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