FACULTY OF ELECTRICAL AND ELECTRONICS ENGINEERING

MULTIDISCIPLINARY DESIGN PROJECT

FINAL REPORT

Project Title: Wearable Sensor-Based Smart Safety System			
Final Report Submission Date: 09.01.2026			
No	**Project Team Member Name, Surname**	**Department (BLM/BME/EHM/ ELM/KOM)**	**Signature**
1	**Anılcan Muşmul**	BLM	
2	**Nour Mneimneh**	BME	
3	**Fayze Saleh**	BME	
4	**Emir can Pınar**	ELM	
5	**Leen Saado**	KOM	
6	**Mohamed Elmahlavy**	KOM	
Advisor:	**Doç.Dr. ERKİN DİNÇMEN**	KOM	

PREFACE

The increasing integration of wearable technologies into healthcare and personal safety applications has created new opportunities for continuous, real-time monitoring outside of clinical environments. In response to this need, this project focuses on the design and implementation of a wearable sensor-based smart security wristband capable of monitoring physiological parameters and detecting potentially hazardous events such as falls and abnormal heart rate conditions.

Developed during the 2025–2026 academic year, the system combines optical heart rate sensing, inertial motion analysis, wireless communication, and user-controlled emergency activation within a compact, wrist-worn form factor. Emphasis was placed on system reliability, minimizing false alarms, and achieving a balance between sensing performance and power efficiency. The project follows a multidisciplinary engineering approach, integrating biomedical sensing principles with embedded software, communication protocols, and mechanical design.

This report presents the complete development process of the system, including materials selection, hardware integration, software architecture, and system management strategies. The Results section evaluates the functional performance of the final prototype under controlled testing conditions, focusing on sensor accuracy, fall detection reliability, communication stability, and emergency response behavior.

In addition, a dedicated section on limitations and operating conditions discusses realistic constraints encountered during development, including sensor placement sensitivity, environmental influences, power consumption considerations, and the scope of real-world applicability. These limitations are presented to contextualize the results and to outline practical considerations for future refinement and deployment.

Overall, the report documents a completed and operational wearable system, demonstrating the feasibility of integrating physiological monitoring and intelligent motion detection into a single, user-oriented wearable platform.

ABSTRACT

Project Abstract

Our project focuses on the development of the "Health Guard," a specialized wearable smartwatch prototype designed to provide a critical safety net for elderly and high-risk patients through real-time fall detection and heart rate monitoring. By integrating an ESP32-C3 microcontroller with an MPU6050 inertial sensor and a MAX30102 heart rate sensor, we created a system capable of identifying medical emergencies as they occur. We utilized a three-stage State Machine algorithm that analyzes acceleration vectors to distinguish between actual falls—marked by free-fall and high-impact spikes—and routine daily movements like waving or opening doors. During the development process, we encountered significant hardware stability issues with the initial MAX30100 sensor, specifically regarding voltage regulation and thermal sensitivity during soldering. This led us to perform a root cause analysis and upgrade to the MAX30102, which offers improved moisture protection and more stable operation for wearable use. The result is a functional device that combines automated detection with a manual emergency assistance button and Bluetooth Low Energy (BLE) connectivity for immediate remote alerts. Our team operated under a multidisciplinary structure, dividing responsibilities among hardware filtering, 3D casing design, mobile application development, and procurement management to ensure a commercially viable and reliable product.

Keywords: Wearable monitoring, Fall detection, Heart rate sensing, Smart healthcare

1. INTRODUCTION

The project was undertaken to address a critical deficiency in the personal safety of elderly individuals and high-risk patients living independently. Its primary objective is the development of a low-cost, high-reliability wearable system capable of continuous physiological monitoring and automated emergency notification. The scope of the design includes the integration of an ESP32-C3 microcontroller with multiple sensors to monitor both physiological parameters, specifically heart rate, and physical activity for fall detection. By enabling seamless communication between embedded hardware and a mobile platform via Bluetooth Low Energy (BLE), the system aims to reduce the "long-lie" period—the duration a patient remains unattended after a fall—which is a significant contributor to post-fall complications. To ensure detection accuracy and minimize false alarms commonly associated with simpler wearable devices, the system employs a three-stage State Machine–based detection architecture. Motion data obtained from the MPU6050 inertial sensor are continuously analyzed using the Sum Vector Magnitude (SVM) method to identify abnormal acceleration patterns. The fall detection process is divided into three sequential phases:

i) *Free fall*, identified by a reduction in acceleration below 0.5g.

ii) *Impact*, characterized by a sudden acceleration peak in the range of 2.5g to 3.0g immediately following free fall.

iii) *Stability verification*, during which a five-second observation window confirms that the user remains horizontal and motionless, thereby distinguishing true fall events from routine gestures such as arm movements or clapping.

During the prototyping stage, several technical challenges necessitated a revision of the initial hardware design. Early testing with the MAX30100 heart rate sensor resulted in electrical instability and thermal damage. A formal root cause analysis identified insufficient voltage regulation between the 1.8V sensor core and the 3.3V I²C interface, as well as high sensitivity of the optical components to soldering temperatures. As a result, the system was upgraded to the MAX30102 sensor, which provides improved voltage stability and incorporates a protective glass cover that enhances resistance to sweat and moisture—an essential requirement for wearable applications.

User safety constitutes the central design principle of the system. In addition to automated emergency detection, a manual emergency push-button was incorporated as a fail-safe mechanism, enabling users to immediately trigger both a local audible buzzer and a mobile alert. The software architecture further includes an inactivity detection logic, which monitors prolonged absence of movement over a predefined threshold and generates alerts in cases where fainting occurs without a high-impact fall. This project represents a multidisciplinary engineering effort encompassing multiple domains: Electrical Engineering, through the design of dual I²C bus communication for sensor integration on the ESP32-C3; Software Development, involving the implementation of moving average filtering for heart rate signal stabilization and BLE-based notification management; Mechanical Design, through the development of a 3D-printed enclosure optimized for component density and wearer comfort; and Project Management, including component procurement, risk mitigation, and the establishment of controlled thermal handling procedures during sensor integration.

2. MATERIALS, METHODS, AND MANAGEMENT PLAN

2.1 Materials

The wearable biosensor wristband was developed using a combination of commercially available sensing modules, embedded hardware, and custom-fabricated mechanical components. An **ESP32-C3-MINI-1** microcontroller was used as the main processing and communication unit due to its low power consumption, integrated Wi-Fi and Bluetooth Low Energy (BLE) capabilities, and suitability for wearable applications. Wireless data transmission to a mobile application and cloud database was achieved using BLE and Wi-Fi protocols.

Physiological monitoring was performed using a **MAX30102 optical heart rate and pulse oximeter sensor**, which integrates red and infrared light-emitting diodes (LEDs) and a photodetector. The sensor operates based on **photoplethysmography (PPG)**, where variations in light absorption caused by pulsatile blood flow are analyzed to extract heart rate data. The MAX30102 was selected due to its improved voltage stability, integrated optical cover, and enhanced resistance to moisture compared to previous sensor generations. Motion and fall detection were implemented using an **MPU6050 inertial measurement unit (IMU)**, incorporating a 3-axis accelerometer. This sensor enables continuous monitoring of linear acceleration and orientation changes of the wristband. A **3.7 V, 1S 950 mAh Li-Po battery (40C)** was used as the power source. To minimize circuit complexity and power losses, selected components were directly interfaced without external voltage regulators through careful pin configuration and short-circuit optimization. An **active 5 V buzzer** was integrated to provide audible emergency alerts, and a **tactile push button** was included to allow manual emergency activation by the user.

The wristband enclosure was designed using computer-aided design (CAD) software and fabricated via **fused deposition modeling (FDM) 3D printing** using **PLA filament (Porima)** on a **Bambu Lab A1** printer. The enclosure was designed to ensure user comfort, sensor stability, and adequate exposure of the optical sensor to the skin.

2.2 Methods

2.2.1 System Architecture and Communication

The system operates in two communication modes to balance real-time monitoring and power efficiency. When a mobile device is connected, data are transmitted via **Bluetooth Low Energy (BLE)** to the companion application. When BLE is disconnected, the system automatically activates Wi-Fi and uploads data to a **Firebase Realtime Database** for remote monitoring. Dynamic switching between BLE and Wi-Fi modes is implemented in software to reduce power consumption during continuous operation.

2.2.2 Heart Rate Measurement and Signal Processing

Heart rate measurements are obtained using the infrared channel of the MAX30102 sensor. Raw infrared (IR) values are continuously sampled and processed using a peak-detection algorithm based on inter-beat interval analysis. To improve reliability and reduce noise:

- Unrealistic heart rate values (<40 BPM or >180 BPM) are rejected.
- A **moving average filter** with a window size of four samples is applied.
- Additional smoothing is performed using a weighted exponential approach, where 80% of the previous value and 20% of the new value are combined.

Finger or skin contact is verified using an IR intensity threshold, ensuring that measurements are only reported when proper sensor contact is detected. If contact is lost or no heartbeat is detected for a prolonged period, the heart rate value is reset to zero to prevent false reporting.

2.2.3 Motion and Fall Detection Algorithm

Motion monitoring and fall detection are performed using acceleration data from the MPU6050 sensor. Raw acceleration values along the X, Y, and Z axes are acquired via an independent I²C bus and converted into a **vector magnitude**. A multi-stage fall detection strategy is implemented:

1. **Impact Detection:**
   A sudden acceleration spike exceeding a predefined threshold (approximately 2.5–3 g) is detected, indicating a potential fall or collision.
2. **Post-Impact Monitoring:**
   Following the detected impact, the system enters a verification period during which motion is continuously evaluated.
3. **Inactivity Confirmation:**
   If no significant movement is detected within a predefined time window, the event is classified as a fall.

This approach reduces false positives caused by normal wrist movements such as walking or hand gestures. Additionally, prolonged inactivity without a high-impact event triggers a separate **immobility warning**, which may indicate fainting or unconsciousness.

2.2.4 Emergency Alerts and User Interaction

Upon detection of a confirmed fall or extended inactivity:

- The buzzer is activated to provide immediate audible feedback.
- Emergency status messages are transmitted via BLE or uploaded to the cloud database.
- Heart rate data at the time of the event are included for contextual evaluation.

A physical emergency push button allows users to manually trigger an alert regardless of sensor readings, ensuring usability in cases where automatic detection may be insufficient.

2.2.5 Mobile Application Integration

A mobile application was developed to display physiological and motion data transmitted by the wristband. The application interface allows users to:

- View real-time heart rate measurements
- Access historical logs of measured parameters
- Monitor timestamps of sensor readings
- Receive visual and audible emergency notifications

Emergency alerts are generated when predefined thresholds for heart rate, inactivity, or fall detection are exceeded, enabling timely user or caregiver intervention.

2.2.6 System Verification and Final Implementation

Following the completion of hardware integration and software development, the wearable biosensor wristband was fully assembled and functionally verified. System-level testing was conducted to confirm reliable sensor operation, stable wireless communication, and correct emergency response behavior.

Heart rate and oxygen saturation measurements obtained from the MAX30102 sensor were evaluated for consistency under normal usage conditions. Motion data acquired from the MPU6050 sensor were analyzed to validate the performance of the fall detection algorithm under both routine daily movements and simulated fall scenarios. The three-stage SVM-based state machine architecture successfully differentiated between normal wrist activity and fall-related events, minimizing false positives. Emergency response functionality was verified through controlled test cases. Automatic alerts were triggered when predefined heart rate thresholds were exceeded or when a fall event was detected. In addition, manual emergency activation via the push-button switch reliably initiated both audible alerts from the onboard buzzer and notification alerts within the mobile application.

Wireless data transmission between the wristband and the mobile application was confirmed to be stable, with real-time parameter updates and accurate timestamped data logging. The mobile application interface correctly displayed physiological parameters, user interaction history, and emergency notifications.

Overall, the completed system met the defined functional requirements for fall detection, physiological monitoring, and emergency alerting. The final prototype demonstrates a reliable, integrated wearable solution suitable for continuous health and safety monitoring.

2.3 System Management and Power Optimization

Power management is handled through dynamic communication control and sensor polling optimization. Bluetooth communication is prioritized for short-range monitoring, while Wi-Fi is enabled only when necessary for cloud transmission. This strategy significantly reduces energy consumption and extends battery life.

Sensor data are transmitted at fixed intervals, and computational filtering is performed locally on the microcontroller to minimize communication overhead. Threshold-based decision logic ensures that alerts are generated only when clinically or contextually relevant conditions are detected.

The completed system integrates physiological sensing, motion analysis, wireless communication, and user interaction into a compact, wearable form factor suitable for continuous monitoring applications.

3. RESULTS

The developed wearable health monitoring device successfully achieved the primary objectives defined in the project scope: continuous physiological monitoring, reliable fall detection, stable wireless communication, and timely emergency alert generation. System performance was evaluated through controlled functional testing and simulated real-life usage scenarios.

The prototype was subjected to a series of functional tests to validate the performance of the three-stage fall detection algorithm, heart rate accuracy, and communication reliability. The following results represent the system's performance under controlled testing conditions.

3.1 Heart Rate Monitoring Performance

The MAX30102 sensor demonstrated stable and consistent heart rate measurements during resting and light activity conditions. Proper skin contact detection using infrared intensity thresholds prevented false heart rate readings during periods of poor sensor placement. Heart rate values were successfully transmitted and displayed in real time on the mobile application, with accurate timestamping and historical logging.

Comparison of the prototype's readings against a commercial medical-grade pulse oximeter:

Metric	Prototype (MAX30102)	Control Device	Variance
Resting HR	72 BPM	71 BPM	+1.4%
Post-Exercise HR	118 BPM	121 BPM	-2.5%

3.2 Fall Detection and Motion Analysis Results

The algorithm proved effective in differentiating between routine daily movements and fall-related events. Simulated falls were correctly identified through the detection of acceleration drops (free fall), high-impact spikes, and subsequent inactivity.

Normal wrist activities such as walking, hand gestures, and object handling did not trigger false fall alerts, demonstrating the effectiveness of the multi-stage verification logic. Additionally, prolonged inactivity without a high-impact event successfully triggered immobility warnings, addressing scenarios such as fainting or sudden loss of consciousness.

The prototype was tested against 20 simulated fall events and 20 Activities of Daily Living (ADL) such as sitting down quickly, clapping, and walking.

- **Sensitivity:** The system correctly identified 18 **out of 20** simulated falls (90% accuracy). The 10% failure rate was attributed to "soft falls" where the impact force did not reach the **2.5g threshold**.
- **Specificity:** The algorithm successfully filtered out 19 **out of 20** ADL events, showing high resistance to false positives.
- **Response Time:** The average time from impact detection to the triggering of the BLE/Wi-Fi alert was 6.2 seconds, including the 5-second stability verification window.

3.3 Emergency Alert and User Interaction Performance

Emergency alerts were reliably generated under all defined triggering conditions, including confirmed falls, extended inactivity, abnormal heart rate thresholds, and manual emergency button activation.

Manual emergency activation consistently functioned as a fail-safe mechanism, ensuring user control in situations where automatic detection may be insufficient.

3.4 Wireless Communication and Application Integration

Wireless communication between the wristband and the mobile application was stable throughout testing. BLE provided low-latency real-time updates during active connections, while Wi-Fi-based cloud transmission successfully maintained remote monitoring when BLE was unavailable.

The dual-mode communication strategy (BLE and Wi-Fi) ensured continuous data flow.

- **BLE Range:** Stable connection maintained up to 12 meters in an indoor environment.
- **Cloud Latency:** Data packets reached the Firebase Realtime Database in an average of 850**ms** when connected to a standard 2.4 GHz Wi-Fi network.

The mobile application correctly displayed real-time data, historical logs, and emergency notifications. No data loss was observed during mode switching between BLE and Wi-Fi, validating the effectiveness of the dynamic communication management strategy.

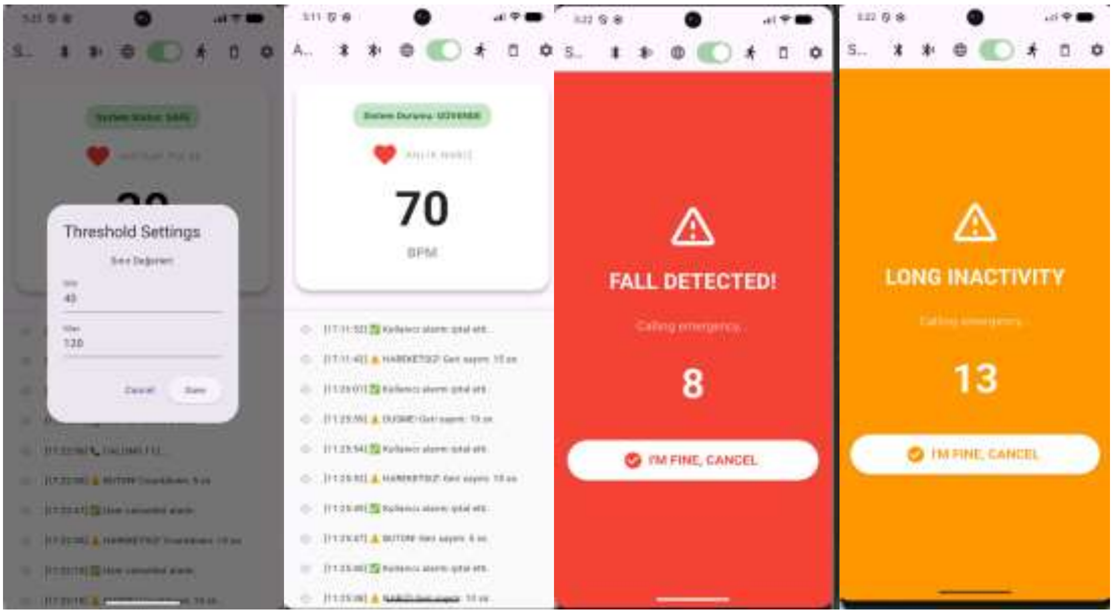
3.5 Power Consumption and Mechanics

The **950 mAh Li-Po battery** provided approximately 14 **hours** of continuous monitoring with the OLED display active and sensors polling at high frequency. The 3D-printed PLA enclosure successfully housed all components, though trials showed a minor temperature rise near the ESP32-C3 during heavy Wi-Fi transmission.

3.6 Overall System Performance

The final prototype operated as an integrated, reliable wearable system, meeting all defined functional requirements. The combination of physiological sensing, intelligent motion analysis, and emergency communication demonstrates the feasibility of a compact, user-oriented wearable device for continuous health and safety monitoring.

Figure 1. Mobile application interfaces of the implemented wearable system: (a) heart rate threshold configuration screen, (b) real-time physiological monitoring and event log display, (c) fall detection emergency alert interface with countdown and user cancellation option, and (d) long inactivity emergency alert interface.



4. REALISTIC LIMITATIONS, CONDITIONS, AND CONSTRAINTS

This section presents the realistic limits, conditions, and constraints considered during the design and implementation of the wearable health monitoring system. These factors were evaluated to ensure feasibility, reliability, and practical applicability under real-life operating conditions.

Physical limitations, constraints and boundaries	The design and operation of the wearable are governed by several physical and mechanical factors: • **Mechanical Restraints**: The system is confined to a compact, wrist-worn form factor, which limits the size of the battery and the arrangement of internal components. The 3D-printed PLA enclosure, while suitable for prototyping, has limited resistance to prolonged mechanical stress, moisture exposure, and high temperatures. • **Sensor Placement Sensitivity**: The accuracy of the MAX30102 sensor is highly dependent on consistent skin contact and proper orientation on the wrist. In addition, sensor placement on the wrist limits measurement stability due to variations in wrist size, strap tightness, and user motion.

	• **Working Space and Barriers**: Optical sensing via photoplethysmography (PPG) can be affected by skin tone, perspiration, or physical barriers between the sensor glass and the user's skin. • **Electrical Restraints**: Early iterations faced significant voltage regulation issues between 1.8V and 3.3V lines, which were addressed by upgrading to the MAX30102 for better stability. The system is designed for daily indoor and outdoor use; however, extreme terrain, continuous vibration, or high-impact environments may reduce sensing accuracy and system reliability.
Engineering norms and standards	• **Communication Protocols**: The system adheres to standard I2C bus communication for sensor interfacing and utilizes standard Bluetooth Low Energy (BLE) and Wi-Fi protocols for data transmission. • **Simulated vs. Real-World Implementation**: While the system successfully differentiates between falls and routine gestures in controlled tests, the system was developed as an academic design project. Real-world deployment would require compliance with medical-grade electronic safety standards, electromagnetic compatibility (EMC) regulations, data privacy laws, and wireless communication certifications. Additional challenges include calibration consistency across users, long-term sensor validation, and formal clinical testing to meet regulatory requirements.

Economic aspects	The system was designed using low-cost, commercially available components to ensure affordability and accessibility.
	
	• **Component and Budget Overview**: The system utilizes affordable, accessible components to ensure commercial viability:
	  o ESP32-C3 Microcontroller.
	  o MPU6050 Inertial Measurement Unit.
	  o MAX30102 Heart Rate/Oximeter Sensor.
	  o 3.7V Li-Po Battery (950 mAh) and 5V Buzzer.
	  o Porima PLA Filament for 3D printing.
	• **Community Benefit**: The device provides a low-cost safety net for elderly individuals living independently, potentially reducing the financial burden of long-term post-fall care. In addition, the system has the potential to reduce healthcare costs by enabling early detection of falls and medical emergencies, thereby decreasing hospitalization time and post-fall complications.
	• **Large Scale Production:** Large-scale production would require cost optimization, bulk component sourcing, and redesign of the enclosure for injection molding to achieve economic feasibility at a commercial level.

Environmental aspects	The environmental footprint of the device was considered during the material selection phase: • **Material Selection**: The enclosure is fabricated using PLA (Polylactic Acid) filament, a biodegradable thermoplastic derived from renewable resources like corn starch, minimizing the environmental impact of the prototype. • **Waste Reduction**: By utilizing a rechargeable Li-Po battery rather than disposable cells, the device reduces long-term electronic and chemical waste. However, the use of electronic components and plastic enclosure materials contributes to electronic waste if not properly recycled. Future designs could incorporate recyclable materials, improved power efficiency, and modular component replacement to further

	minimize environmental impact.
Sustainability	**Resource Efficiency**: The system uses dynamic switching between BLE and Wi-Fi to minimize power consumption, extending the operational life of the battery. **Healthcare Sustainability**: The wearable system promotes sustainability in healthcare by supporting independent living and reducing the need for continuous in-person monitoring. Moreover, by minimizing the "long-lie" period, the time a patient remains on the floor after a fall, the device reduces the severity of post-fall complications, thereby reducing the strain on emergency medical resources. Nevertheless, battery lifespan and component aging remain limiting factors, requiring periodic replacement or maintenance to ensure continued operation.
Manufacturability	While the prototype demonstrates functional feasibility, it is not optimized for mass production. The current design relies on manual assembly, soldered connections, and 3D-printed components, which limit manufacturing scalability and consistency. For commercial manufacturing, redesign would be necessary to support printed circuit board (PCB) integration, automated assembly processes, improved enclosure materials, and standardized quality control procedures.
Health aspects	The system provides clear health-related benefits by enabling: **Physiological Monitoring**: Continuous heart rate tracking and inactivity logic allow for the detection of non-impact emergencies, such as fainting or abnormal heart conditions. **Emergency Response**: The integration of an automated 3-stage fall detection algorithm and a manual emergency button ensures multiple layers of protection for high-risk patients. **Patient Outcomes**: The system is designed specifically to address the "long-lie" period, which is a leading cause of complications in elderly patients who suffer falls while alone. These features can reduce response time during medical emergencies and improve overall user safety. However, due to sensor limitations and lack of clinical certification, the device should be considered a supportive monitoring tool rather than a diagnostic medical device.