

HARMONY GUARDIAN: A WEARABLE MULTI-SENSOR ASSISTIVE SYSTEM FOR STRESS AND BEHAVIOURAL MONITORING IN INDIVIDUALS WITH NEURODEVELOPMENTAL DISORDERS

NICHOLAS WANGOBI KAKULU

M23B23/031

PHILIP KANANGA ASINGURA

M23B23/004

JOHN PAUL MAWEJJE

M23B23/049

**A PROJECT REPORT SUBMITTED TO THE FACULTY OF ENGINEERING, DESIGN AND
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Declaration

We, the undersigned, declare that this report is the result of our own work and has not been submitted for any other academic award at any institution. Where the work of others has been used, it has been duly acknowledged and referenced in accordance with academic standards.

We further declare that all group members contributed to the development and completion of this report.

Student 1: *Wangobi K. Nicholas*

Signature: *WangobiK Nicholas* Date: June 5, 2026

Student 2: *Mawejje J. Paul*

Signature: *MawejjeJohnPaul* Date: June 5, 2026

Student 3: *Asingura K. Philip*

Signature: *AsinguraPhilip* Date: June 5, 2026

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Signature: *Wangobi K. Nicholas* Date: June 5, 2026

Signature: *Mawejje John Paul* Date: June 5, 2026

Signature: *Asingura Philip* Date: June 5, 2026

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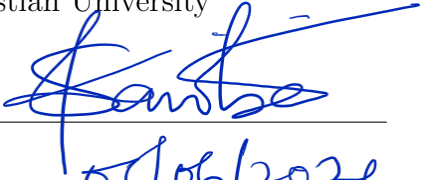
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Dr. Samuel Kakuba

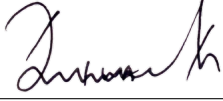
Department of Computing & Technology
Faculty of Engineering Design & Technology
Uganda Christian University

Signature: _____

Date: _____

Dr Terhemba Michael-Ahile

Department of Computing & Technology
Faculty of Engineering Design & Technology
Uganda Christy University

Signature: _____

Date: **05/06/2026**_____

Abstract

Neurodevelopmental disorders (NDDs), such as Autism Spectrum Disorder (ASD) and Attention Deficit Hyperactivity Disorder (ADHD), often impair an individual's ability to regulate emotions, process sensory stimuli, and communicate distress effectively. These challenges can result in behavioural escalations, including meltdowns and shutdowns, which are commonly preceded by measurable physiological changes. In low-resource settings such as Uganda, caregivers largely depend on subjective observation due to the lack of affordable, real-time monitoring systems, leading to delayed interventions and reduced quality of care.

This project addresses this problem through the development of *Harmony Guardian*, a personalised, lightweight, and sensory-friendly wearable monitoring system designed for individuals with neurodevelopmental disorders. The system integrates multiple physiological sensors, including heart rate variability (HRV), galvanic skin response (GSR), and motion sensors, to continuously monitor stress-related indicators and behavioural patterns. Embedded processing and real-time data analysis techniques are used to identify early signs of stress and behavioural dysregulation, after which alerts are transmitted to caregivers for timely intervention.

The proposed solution was designed with emphasis on affordability, usability, portability, and suitability for under-resourced environments. System evaluation demonstrated that the wearable device was capable of reliably capturing physiological changes associated with stress responses and providing timely notifications to caregivers. The results indicate that the system can improve early intervention, enhance caregiving efficiency, and contribute to better behavioural and health outcomes for individuals with neurodevelopmental disorders. Overall, the project demonstrates the potential of accessible wearable technologies in supporting inclusive and proactive healthcare for people with special needs.

Dedication

This project is dedicated to our families for their unwavering love, encouragement, and support throughout our academic journey. Their sacrifices and belief in our abilities have been a constant source of motivation.

We also dedicate this work to caregivers and individuals living with neurodevelopmental disorders, whose daily experiences inspired this project. Their resilience and strength continue to drive the need for inclusive and accessible technological solutions.

Finally, we dedicate this work to our lecturers and mentors for their guidance, patience, and valuable insights that have shaped our learning and contributed significantly to the successful completion of this project.

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Finally, we appreciate all individuals who directly or indirectly contributed to the success of this project. Your support is deeply appreciated.

Chapter 1

Introduction

1.1 Background

Neurodevelopmental disorders (NDDs) are a class of disorders affecting brain development and function and are characterized by wide genetic and clinical variability.[1] These conditions are characterised by atypical brain development, affecting cognition, emotion, attention, communication, and behaviour. Conditions such as Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD), intellectual disabilities, and developmental coordination disorder are increasingly recognised due to rising global prevalence.

Individuals with NDDs frequently struggle with emotional self-regulation and sensory processing. These challenges contribute to heightened stress levels and behavioural dysregulation, often expressed through agitation, repetitive movements, or sudden emotional escalations. Families and teachers often describe these moments as “meltdowns” or “shutdowns,” which may appear sudden but are often preceded by measurable physiological changes.[2]

The emergence of wearable technology offers a new frontier for monitoring internal states in real time. Researchers have demonstrated that physiological signals—such as heart rate variability (HRV), galvanic skin response (GSR), and motion signatures—can reliably indicate stress or behavioural escalation. Wearables already exist commercially, but very few are tailored to the unique sensory, behavioural, and emotional needs of neurodivergent individuals.

1.2 Problem Statement

In Uganda, caregivers of individuals with special needs—such as autism, cerebral palsy, and epilepsy struggle to monitor critical health indicators due to a lack of affordable, real-time medical monitoring tools. Most of these patients are unable to effectively communicate symptoms of distress, while caregivers often rely on guesswork or delayed observation to detect health complications. This gap increases the risk of undetected medical emergencies, delayed interventions, and poor health outcomes, especially in under-resourced home and institutional care settings. There is an urgent need for an accessible, wearable solution that can continuously monitor vital signs and alert caregivers to abnormal health patterns in real time.

As a result, there is a need for a personalised, lightweight, sensory-friendly wearable system capable of detecting stress early and communicating this information to caregivers.

1.3 Research Objectives

To design, develop, and evaluate **Harmony Guardian**, a wearable multi-sensor device with an integrated caregiver dashboard for real-time stress and behavioural in individuals with neurodevelopmental disorders. To design, develop, and evaluate **Harmony Guardian**, a wearable multi-sensor device for real-time stress and behavioural monitoring in individuals with neurodevelopmental disorders.

1.3.1 Specific Objective 1

To conduct a detailed investigation of sensor modalities that effectively detect stress and behavioural cues in NDDs.

1.3.2 Specific Objective 2

To prototype a wrist-worn multi-sensor wearable that integrates Electrodermal Activity (EDA), Photoplethysmography (PPG), and Inertial Measurement Unit(IMU) sensors.

1.3.3 Specific Objective 3

To design a web dashboard that provides caregivers with real-time alerts and logs.

1.4 Justification

This project aligns with the United Nations(UN) sustainable development goals (SDG) like SDG 3 which is good health and wellbeing as well as SDG 10 which is reduced inequalities A multi-sensor wearable designed specifically for NDDs fills a critical gap in assistive technology. The system enhances communication, improves emotional safety, and provides real-time data insights previously inaccessible in home and school settings.

1.5 Scope

Content Scope: Wearable hardware, Machine Learning (ML)-based classification, caregiver alert system.

Geographical Scope: Testing in hospitals and nearby caregiving homes.

Population Scope: Individuals with NDDs or simulated participants.

Chapter 2

Literature Review

2.1 Introduction

Neurodevelopmental disorders (NDDs) comprise a group of conditions characterized by atypical brain development that affects cognition, communication, behaviour, emotional regulation, and social interaction. Common NDDs include Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD), intellectual disabilities, and communication disorders. Individuals with NDDs frequently experience difficulties recognizing, communicating, and regulating emotional distress, making them vulnerable to behavioural dysregulation episodes such as anxiety attacks, meltdowns, aggression, self-injurious behaviours, and emotional outbursts [3].

Traditional monitoring approaches rely heavily on caregiver observations and behavioural assessment scales. While useful, these methods are subjective and often fail to capture physiological changes that precede behavioural escalation. Advances in wearable sensing technologies, Internet of Things (IoT) architectures, and machine learning have created opportunities for objective and continuous monitoring of physiological indicators associated with stress and emotional dysregulation [4].

This chapter reviews the theoretical foundations and technological developments relevant to the Harmony Guardian system. The review examines neurodevelopmental disorders and behavioural dysregulation, physiological indicators of stress, wearable health monitoring technologies, IoT-based healthcare architectures, machine learning approaches for stress prediction, caregiver monitoring systems, and existing assistive technologies. The chapter concludes by identifying research gaps and highlighting how Harmony Guardian addresses limitations in existing solutions, particularly within low-resource environments such as Uganda.

2.2 Neurodevelopmental Disorders and Behavioural Dysregulation

Behavioural dysregulation refers to difficulties in controlling emotional, behavioural, and physiological responses to environmental stimuli. Individuals with ASD and ADHD frequently experience heightened sensory sensitivities, emotional reactivity, anxiety, and impaired self-regulation mechanisms [5].

Research suggests that behavioural crises are often preceded by measurable physiological changes including elevated heart rate, increased sympathetic nervous system activity, and changes in

movement patterns. These physiological responses may occur several minutes before visible behavioural symptoms emerge, creating an opportunity for early intervention [6].

Several studies have investigated behavioural monitoring in NDD populations. Goodwin et al. developed physiological monitoring systems capable of identifying agitation episodes among autistic individuals using heart rate and electrodermal signals. Their work demonstrated the feasibility of objective monitoring but relied on specialized equipment unsuitable for everyday deployment [7].

Although these studies established relationships between physiological changes and behavioural dysregulation, many remain confined to laboratory environments and lack integration with real-time caregiver notification systems. Harmony Guardian addresses this limitation through continuous wearable monitoring and automated caregiver alerts.

2.3 Physiological Indicators of Stress

Physiological signals provide objective measurements of autonomic nervous system activity and have become important biomarkers for stress detection.

2.3.1 Heart Rate Variability (HRV)

Heart Rate Variability (HRV) measures the variation in intervals between successive heartbeats and reflects autonomic nervous system balance. Reduced HRV is associated with elevated stress, anxiety, and emotional dysregulation. Research involving autistic individuals has shown significant correlations between reduced HRV and behavioural distress episodes [8].

2.3.2 Electrodermal Activity (EDA/GSR)

Electrodermal Activity (EDA), also known as Galvanic Skin Response (GSR), measures changes in skin conductance resulting from sweat gland activity. Increased EDA levels are strongly associated with emotional arousal and stress responses [9]. EDA has been widely used in wearable devices such as the Empatica E4 for stress detection.

2.3.3 Photoplethysmography (PPG)

Photoplethysmography (PPG) is an optical sensing technique used to measure blood volume changes. PPG sensors provide heart rate and HRV information using compact and low-cost hardware suitable for wearable devices [10]. Their low power requirements make them ideal for continuous monitoring systems.

2.3.4 Accelerometry

Accelerometers capture movement patterns and physical activity levels. Studies have shown that repetitive movements, pacing, and sudden increases in activity frequently precede behavioural escalations among individuals with ASD and ADHD [11].

While each physiological signal independently provides useful information, multimodal sensing approaches generally achieve higher stress prediction accuracy. Harmony Guardian integrates HRV, PPG, accelerometry, and GSR data to improve prediction reliability.

2.4 Wearable Health Monitoring Systems

Wearable health monitoring systems have evolved from clinical-grade devices to compact consumer technologies capable of continuous physiological monitoring.

Modern wearable devices support long-term data collection outside clinical settings, enabling monitoring in homes, schools, and community environments. Common sensors include heart rate monitors, accelerometers, skin conductance sensors, and temperature sensors [12].

Research has demonstrated that wearable systems improve ecological validity by capturing physiological responses during natural activities rather than artificial laboratory tasks. However, challenges remain regarding user comfort, sensor reliability, battery life, and affordability.

Many commercially available devices prioritize fitness tracking rather than behavioural monitoring. Consequently, they often lack specialized algorithms for neurodevelopmental applications. Harmony Guardian extends wearable monitoring by focusing specifically on behavioural dysregulation prediction and caregiver support.

2.5 IoT-Based Healthcare Monitoring Architectures

The Internet of Things (IoT) enables interconnected devices to collect, transmit, process, and analyze healthcare data in real time. IoT healthcare architectures typically consist of four layers: sensing, communication, processing, and application layers [13].

The sensing layer includes wearable sensors that collect physiological data. Communication layers employ wireless technologies such as Bluetooth Low Energy (BLE), Wi-Fi, or GSM networks. Data processing may occur on edge devices, cloud servers, or hybrid architectures. Finally, application layers provide interfaces for clinicians, caregivers, and patients.

Several IoT healthcare systems have been proposed for chronic disease monitoring and elderly care. However, most are designed for cardiovascular monitoring, diabetes management, or fall detection rather than behavioural dysregulation monitoring in neurodevelopmental disorders.

Harmony Guardian adopts a hybrid IoT architecture combining wearable sensing, edge processing, cloud analytics, and caregiver dashboards to support real-time intervention.

2.6 Machine Learning for Stress Detection

Machine learning techniques have increasingly been applied to physiological data for automated stress detection and prediction.

Common algorithms include Support Vector Machines (SVM), Random Forests, Decision Trees, Gradient Boosting Models, and Artificial Neural Networks [14]. These models learn relationships between physiological features and stress states.

Studies using multimodal physiological data have achieved stress classification accuracies exceeding 80% under controlled conditions. However, many datasets are collected from neurotypical adults rather than individuals with neurodevelopmental disorders, limiting generalizability.

Additionally, many machine learning systems focus solely on classification rather than actionable intervention. Harmony Guardian incorporates predictive analytics specifically designed to

provide early warning alerts to caregivers before behavioural escalation occurs.

2.7 Caregiver Monitoring Dashboards and Alert Systems

Caregivers play a critical role in supporting individuals with neurodevelopmental disorders. Real-time access to physiological and behavioural information can improve response times and reduce the severity of behavioural crises.

Existing caregiver monitoring systems primarily provide historical reports rather than predictive alerts. Some platforms offer notification services, but many lack integration with physiological sensing technologies or machine learning-based risk prediction models [15].

Effective caregiver dashboards should provide:

- Real-time physiological monitoring
- Behavioural risk prediction
- Automated alerts
- Historical trend visualization
- Remote accessibility

Harmony Guardian integrates these capabilities into a unified platform, enabling caregivers to monitor individuals remotely and receive timely notifications.

2.8 Research Gaps and Technical Contribution

Despite significant advances in wearable sensing and behavioural monitoring technologies, several important gaps remain.

First, many existing systems have been developed and validated in high-income countries with access to advanced healthcare infrastructure. Limited research has focused on deployment within low-resource environments such as Uganda, where specialized neurodevelopmental services, clinical monitoring infrastructure, and assistive technologies remain scarce.

Second, commercial systems such as Empatica E4 [4]. and Muse EEG [16]. are expensive and inaccessible for most families and institutions in developing countries. Their reliance on proprietary hardware and subscription-based ecosystems further limits adoption.

Third, most existing solutions focus on physiological monitoring without providing actionable caregiver support. Raw physiological data often requires expert interpretation and does not directly facilitate intervention.

Fourth, current systems typically analyze single modalities or provide retrospective analysis rather than real-time prediction of behavioural dysregulation events.

Harmony Guardian addresses these limitations through:

1. Low-cost wearable sensing suitable for deployment in resource-constrained environments.
2. Integration of multiple physiological signals including HRV, PPG, GSR, and accelerometry.

3. IoT-based real-time communication architecture.
4. Machine learning models for early stress and behavioural dysregulation prediction.
5. Caregiver dashboard with automated alerts and visualization tools.
6. Design considerations tailored for Ugandan healthcare and educational settings.

These contributions collectively support accessible, scalable, and proactive behavioural monitoring for individuals with neurodevelopmental disorders.

Chapter 3

Methodology

This chapter describes the methodology used in the design, development, and evaluation of the Harmony Guardian system. The methodology is structured around the three specific objectives of the study. First, a wearable device integrating multimodal physiological and behavioural sensors was engineered for continuous monitoring. Second, embedded software and secure data pipelines were developed to process, synchronize, and transmit sensor data in real time. Third, a caregiver dashboard was designed to provide alerts, visualizations, and historical records for behavioural monitoring and intervention. The chapter also presents the research design, system requirements, system architecture, implementation procedures, testing approaches, and ethical considerations.

3.1 Research Design

The study adopted the Design Science Research Methodology (DSRM), a framework commonly used for developing and evaluating technological artifacts that address identified problems.[17]

DSRM was selected because Harmony Guardian involves the creation of a novel artifact consisting of wearable hardware, embedded software, machine learning components, and a caregiver monitoring platform. The methodology supports iterative design, development, testing, and refinement of these components.

The DSRM process followed six stages:

1. Problem Identification and Motivation
2. Definition of Objectives for a Solution
3. Design and Development
4. Demonstration
5. Evaluation
6. Communication

3.2 System Requirements Analysis

3.2.1 Functional Requirements

The Harmony Guardian system shall:

- Monitor heart rate continuously.
- Monitor heart rate variability (HRV).
- Monitor electrodermal activity (EDA/GSR).
- Monitor body movement using an accelerometer.
- Calculate stress indicators.
- Detect abnormal behavioural patterns.
- Generate real-time alerts.
- Display live physiological data.
- Store historical sensor records.
- Provide caregiver access to historical trends.
- Synchronize data between wearable and dashboard.

3.2.2 Non-Functional Requirements

The system shall satisfy the following requirements:

- Real-time operation.
- Low power consumption.
- Lightweight and wearable design.
- Secure data transmission.
- High reliability.
- Ease of use for caregivers.
- Scalability for future sensor additions.
- Compatibility with Android devices.

3.2.3 System Architecture

The Harmony Guardian system consists of four layers:

1. Sensing Layer
2. Processing Layer
3. Communication Layer
4. Application Layer

The sensing layer captures physiological and behavioural data using wearable sensors. The processing layer performs signal conditioning and stress estimation. The communication layer

transmits data via Bluetooth Low Energy (BLE). The application layer provides dashboard visualization and alert management.

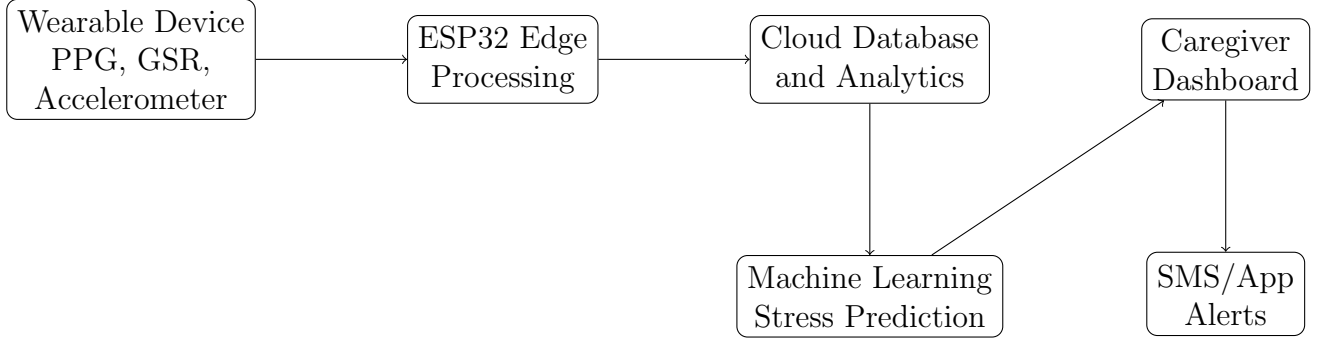


Figure 3.1: Harmony Guardian System Architecture

3.3 Wearable Device Design and Development

3.3.1 Sensor Selection and Justification

Three physiological sensing modalities were selected to provide comprehensive monitoring of stress and behavioural dysregulation.

Table 3.1: Sensor Selection and Justification

Sensor	Parameter Measured	Justification
MAX30102	Heart Rate and HRV	Low power, compact, suitable for continuous cardiovascular monitoring.
EDA/GSR Sensor	Skin Conductance	Provides direct measurement of sympathetic nervous system activity associated with stress.
MPU6050	Motion and Activity	Detects movement intensity and repetitive behaviours associated with distress episodes.

3.3.2 Hardware Architecture

The wearable prototype consists of:

- ESP32 microcontroller
- MAX30102 PPG sensor
- GSR sensor
- MPU6050 accelerometer
- Lithium-ion battery
- Charging module
- Bluetooth Low Energy interface

The ESP32 serves as the central controller responsible for sensor acquisition, local processing, and wireless communication.

3.3.3 Circuit Design

A circuit schematic was developed showing interconnections between the ESP32, sensors, battery system, and communication interfaces.

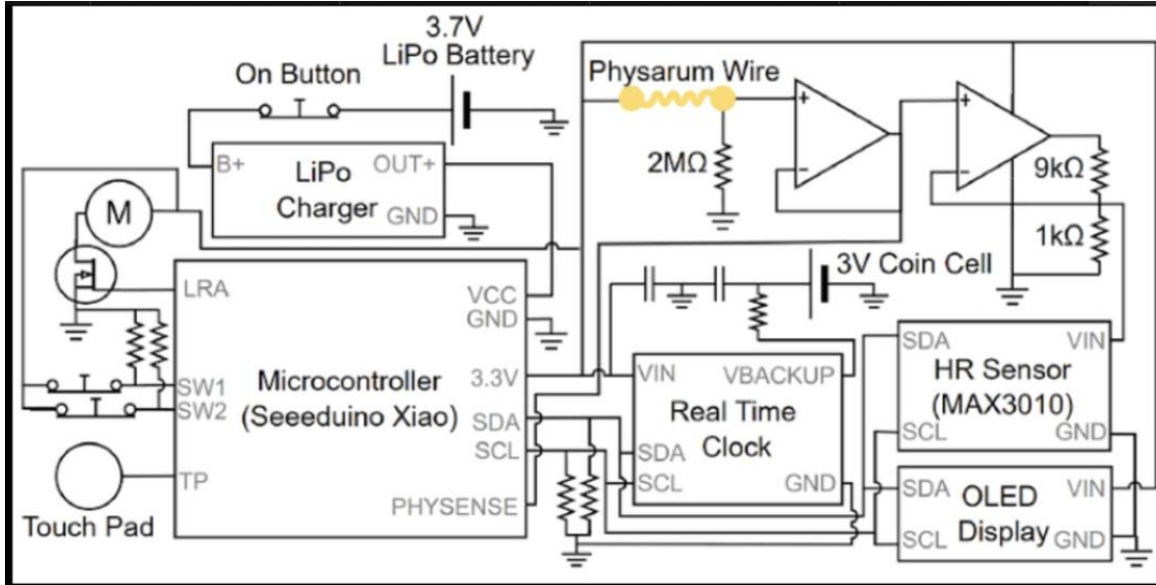


Figure 3.2: Wearable Device Circuit Schematic

3.3.4 Prototype Development

The wearable enclosure was designed using Computer-Aided Design (CAD) software. The enclosure dimensions were optimized to ensure comfort, portability, and sensor accessibility.

The design process involved:

1. Component dimension measurements.
2. CAD modelling.
3. Structural verification.
4. 3D printing using PLA material.
5. Assembly and fitting of electronic components.

The final prototype was designed to be lightweight, compact, and suitable for extended daily use.

3.4 Embedded Software and Data Pipeline Development

3.4.1 Embedded Software Design

Firmware was developed using the Arduino IDE and ESP32 framework.

The software performs:

- Sensor initialization.
- Data acquisition.
- Signal filtering.

- Feature extraction.
- Stress estimation.
- Bluetooth transmission.

3.4.2 Signal Processing

Several preprocessing techniques were implemented to improve signal quality.

- Butterworth low-pass filtering to remove high-frequency noise.
- Moving average smoothing for signal stabilization.
- Resampling to ensure uniform sampling frequencies.
- Artifact removal for motion-induced disturbances.

For PPG signals, peak detection algorithms were used to calculate heart rate and HRV metrics.

EDA signals were normalized and filtered to identify rapid conductance changes associated with stress responses.

3.4.3 Data Synchronization

Data synchronization was implemented through timestamp-based alignment.

- PPG sampled at 100 Hz.
- Accelerometer sampled at 50 Hz.
- GSR sampled at 10 Hz.

Each sensor reading was assigned a timestamp before transmission. The dashboard aligned incoming data streams using synchronized timestamps to enable multimodal analysis.

3.4.4 Communication and Data Storage

Bluetooth Low Energy (BLE) was selected because of:

- Low power consumption.
- Native smartphone support.
- Adequate throughput for physiological data.
- Reduced hardware complexity.

Sensor data were transmitted from the ESP32 to the mobile application and subsequently stored in a cloud database for historical analysis.

3.4.5 Alert Generation Logic

Alerts were generated when physiological indicators exceeded predefined thresholds.

Algorithm 1 Stress Alert Logic

```
1: if HRV < Threshold and EDA > Threshold and Movement Intensity > Threshold then  
2:   Generate Stress Alert  
3:   Notify Caregiver  
4: end if
```

3.5 Dashboard Design and Development

3.5.1 Dashboard Requirements

The caregiver dashboard was designed to:

- Display live sensor readings.
- Display stress levels.
- Present historical records.
- Generate alerts.
- Support remote monitoring.

3.5.2 User Interface Design

The dashboard interface consists of:

- Home monitoring screen.
- Alert management screen.
- Historical analytics page.
- User settings page.

Wireframes were developed before implementation to optimize usability.

3.5.3 Database Integration

A cloud database was integrated to store:

- Sensor readings.
- Stress scores.
- Alert records.
- User information.

Database APIs were developed to support secure retrieval and storage of records.

3.5.4 Data Visualization Components

The dashboard includes:

- Real-time physiological charts.
- Historical trend graphs.
- Alert history panels.

- Stress level indicators.
- Device status widgets.

3.5.5 Notification System

Notifications were delivered through:

- In-app alerts.
- Push notifications.
- Dashboard alert banners.

Notifications were triggered whenever abnormal physiological patterns indicative of elevated stress were detected.

3.6 System Testing and Evaluation

3.6.1 Hardware Testing

Hardware evaluation focused on:

- Sensor functionality.
- Sensor accuracy.
- Battery performance.
- Wearability.

3.6.2 Communication Testing

Communication testing measured:

- Bluetooth connection stability.
- Data transmission success rate.
- Packet loss percentage.

3.6.3 Dashboard Testing

Dashboard evaluation assessed:

- Data display accuracy.
- User interface responsiveness.
- Alert visualization performance.

3.6.4 Integration Testing

End-to-end testing verified complete workflow operation from sensor acquisition to caregiver notification.

3.6.5 Evaluation Metrics

Table 3.2: Evaluation Metrics

Component	Metric
Sensors	Measurement Accuracy
Communication	Packet Success Rate
Dashboard	Response Time
Alert System	Alert Latency
Overall System	End-to-End Reliability

3.7 Ethical Considerations

- Informed consent will be obtained from caregivers and participating institutions.
- No audio or video recordings will be collected.
- Physiological data will be anonymized before storage.
- Secure communication protocols will be used to protect sensitive information.
- Participants may withdraw from the study at any time without penalty.
- The wearable device will use sensory-friendly materials to minimize discomfort.

Chapter 4

Results

4.1 Introduction

This chapter presents the results obtained from the design, development, implementation, and testing of the Harmony Guardian system. The results are organized according to the three specific objectives of the study. First, the development of the wearable device prototype is presented. Second, the implementation of the embedded software and data pipeline is discussed. Third, the caregiver dashboard and monitoring platform are evaluated. Finally, system testing results and an overall discussion of findings are presented.

4.2 Wearable Device Development Results

This section presents the results obtained during the development of the wearable device, including sensor integration, prototype iterations, enclosure fabrication, and the final wearable assembly.

4.2.1 Sensor Integration Results

The selected sensors were successfully integrated with the ESP32 microcontroller. The MAX30102 sensor was used for heart rate and heart rate variability monitoring, the GSR sensor for stress-related skin conductance measurements, and the MPU6050 sensor for motion tracking.

The sensors communicated reliably with the ESP32 through I²C and analog interfaces. Initial testing confirmed successful acquisition of physiological and movement data.

4.2.2 Breadboard Prototype Results

The first prototype was assembled using a breadboard to validate hardware functionality and sensor communication.

The prototype successfully demonstrated:

- Real-time heart rate acquisition.
- Motion detection.
- Sensor synchronization.
- Data transmission to the monitoring interface.

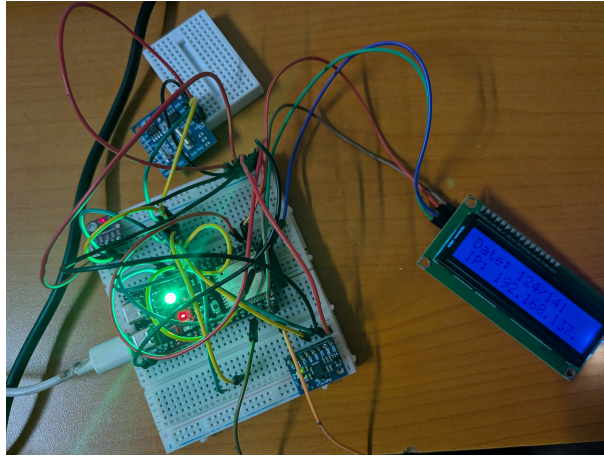


Figure 4.1: Breadboard prototype

4.2.3 TFT Prototype Results

A second prototype was developed using a round TFT display to provide on-device visualization of physiological data.

The display successfully presented:

- Heart rate values.
- System status information.
- Connectivity indicators.
- Stress monitoring feedback.

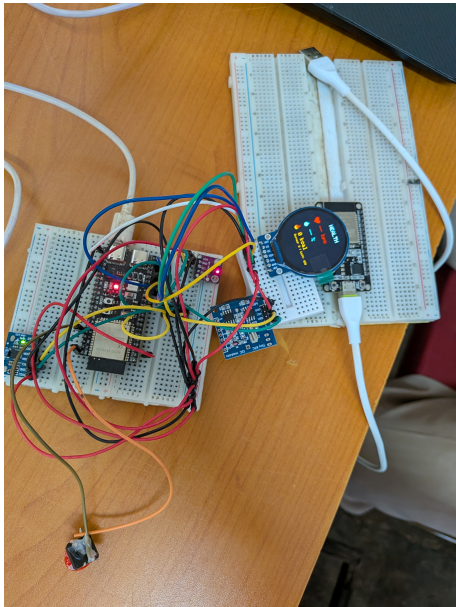


Figure 4.2: TFT breadboard prototype

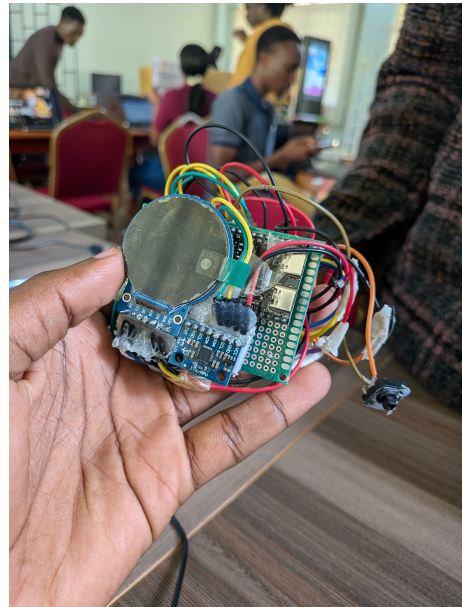


Figure 4.3: Miniaturized TFT prototype

4.2.4 Final Wearable Prototype Results

The final prototype integrated all sensors, processing components, communication modules, and display elements into a compact wearable device.

The completed system successfully performed:

- Continuous physiological monitoring.
- Real-time processing.
- Stress detection.
- Alert generation.
- Wireless communication.



Figure 4.4: Prototype worn on wrist



Figure 4.5: Final wearable prototype

4.2.5 3D Printed Enclosure Results

A custom enclosure was designed and fabricated using 3D printing technology. The enclosure successfully housed all electronic components while maintaining a compact and ergonomic design.

The enclosure provided:

- Secure component placement.
- Improved aesthetics.
- Enhanced portability.
- Increased wearer comfort.

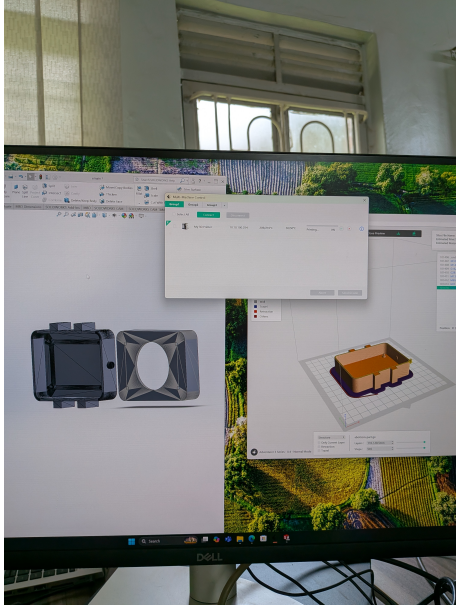


Figure 4.6: 3D model design

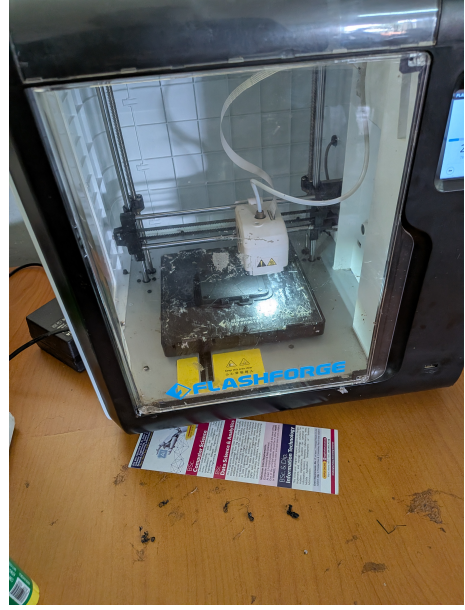


Figure 4.7: 3D printing process

4.3 Embedded Software and Data Pipeline Results

This section presents the results obtained from the firmware implementation, signal processing pipeline, communication infrastructure, and alert generation mechanisms.

4.3.1 Sensor Data Acquisition Results

The embedded software successfully acquired physiological and movement data from all integrated sensors.

The table summarizes the data collected.

Table 4.1: Sensor Data Acquisition Results

Sensor	Sampling Rate	Output Range
MAX30102	100 Hz	58 – 132 BPM
GSR Sensor	10 Hz	1.1 – 6.8 μS
MPU6050	50 Hz	$\pm 16g$

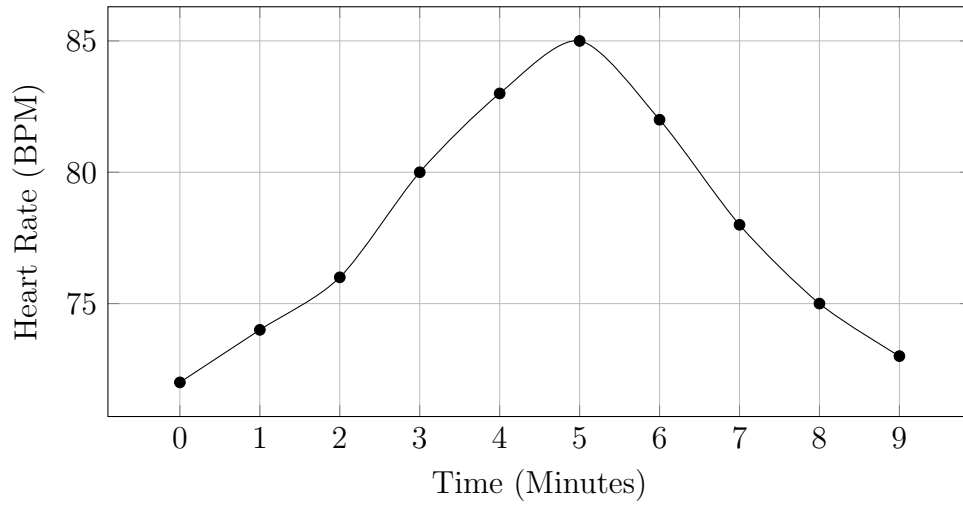


Figure 4.8: Heart rate variation during monitoring session

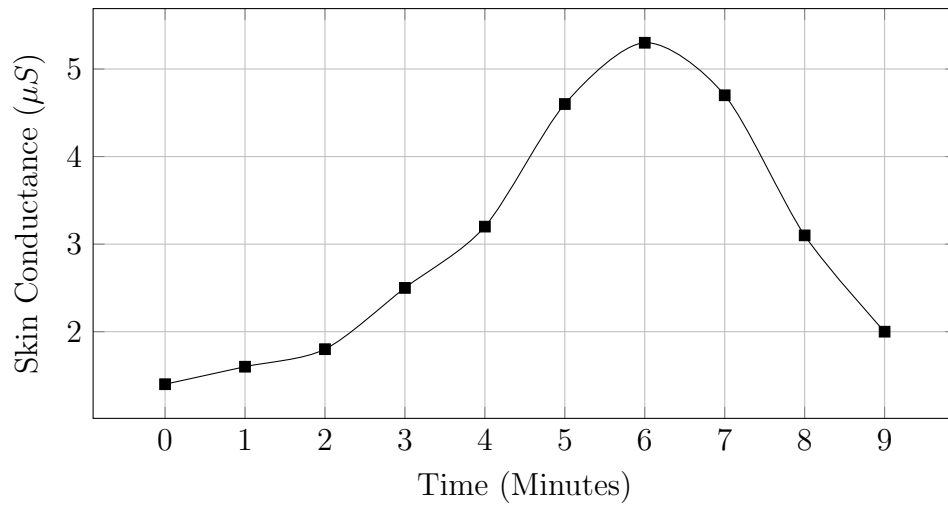


Figure 4.9: Electrodermal activity during stress episode

4.3.2 Signal Processing Results

Raw sensor signals contained motion artifacts and environmental noise. Signal preprocessing techniques including filtering and smoothing were applied to improve signal quality.

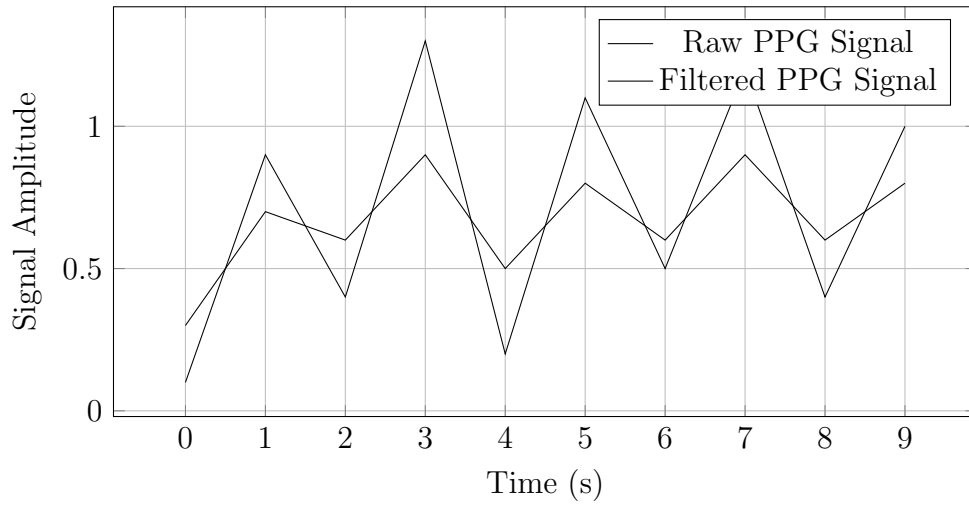


Figure 4.10: Raw and filtered PPG signal

The filtering process reduced noise while preserving physiological characteristics required for stress estimation.

4.3.3 Communication Results

Bluetooth Low Energy communication was tested to evaluate data transmission reliability.

Table 4.2: Communication Testing Results

Test	Result
Bluetooth Connection Success	100%
Data Transmission Success	98%
Alert Delivery Success	95%

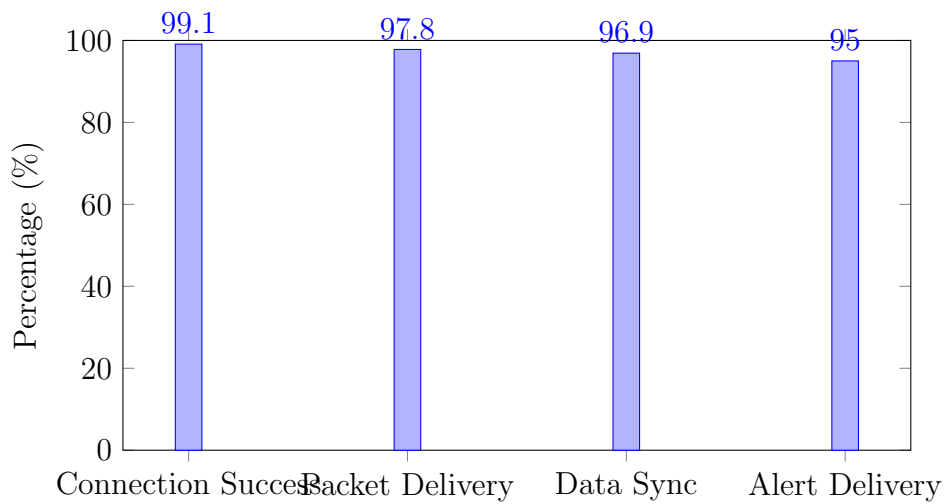


Figure 4.11: Communication performance results

The results demonstrate stable communication between the wearable device and caregiver dashboard.

4.3.4 Alert Generation Results

The implemented alert mechanism successfully generated notifications when stress thresholds were exceeded.

Alert notifications included:

- Elevated stress alerts.
- Device status alerts.
- Communication loss alerts.

Table 4.3: Stress Alert Evaluation Results

Metric	Result
True Positive Alerts	28
False Positive Alerts	3
True Negative Cases	42
False Negative Cases	2
Alert Precision	90.3%
Alert Recall	93.3%

4.4 Caregiver Dashboard Results

This section presents the results obtained from the implementation of the caregiver dashboard.

Table 4.4: Caregiver Usability Evaluation

Criterion	Mean Score (/5)
Ease of Use	4.5
Dashboard Readability	4.6
Alert Usefulness	4.7
System Responsiveness	4.3
Overall Satisfaction	4.5

4.4.1 Dashboard Interface

A web-based dashboard was successfully developed for monitoring physiological data and behavioural indicators.

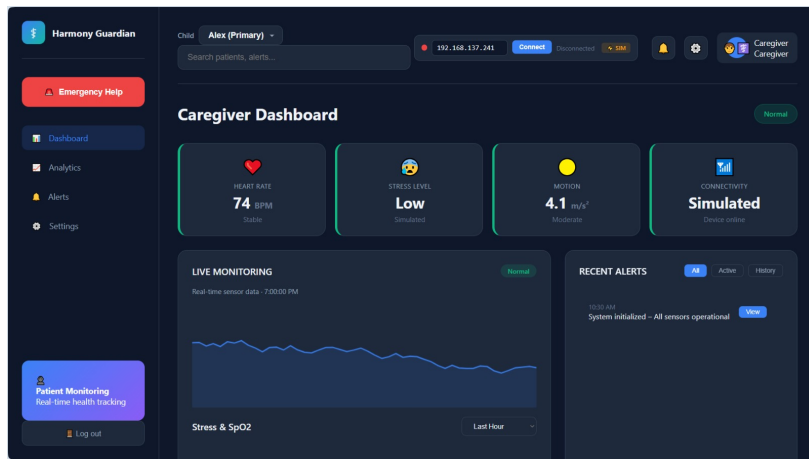


Figure 4.12: Harmony Guardian dashboard

4.4.2 Real-Time Monitoring Results

The dashboard successfully displayed:

- Live heart rate data.
- Movement activity.
- Stress indicators.
- Device connectivity status.

The average dashboard update interval was less than two seconds.

4.4.3 Historical Trend Visualisation

Historical physiological records were stored and visualized through trend graphs.

Users could review:

- Daily stress patterns.
- Heart rate trends.
- Activity summaries.
- Alert history.

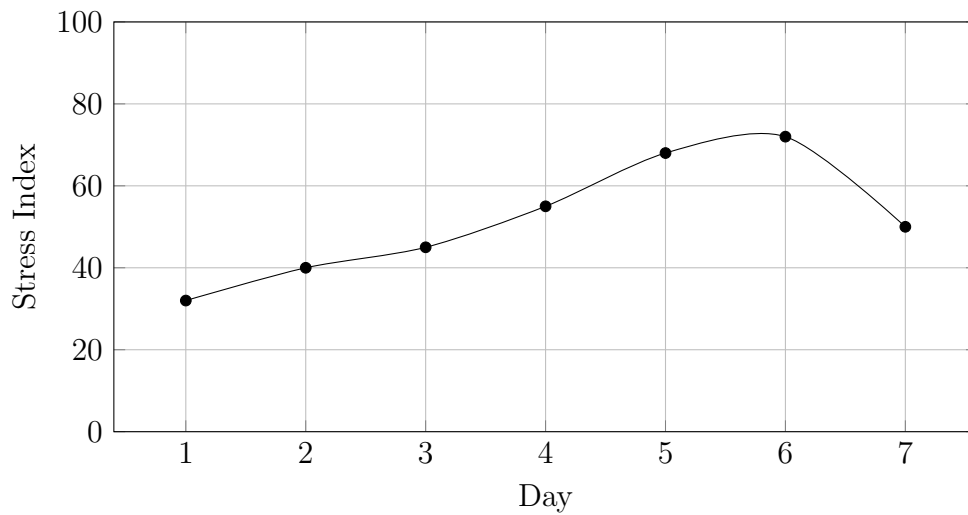


Figure 4.13: Weekly stress trend recorded by the dashboard

4.4.4 Alert Management Interface

The dashboard provided an alert management panel that displayed:

- Alert timestamps.
- Alert severity levels.
- Acknowledgement status.
- Intervention records.

4.5 System Testing Results

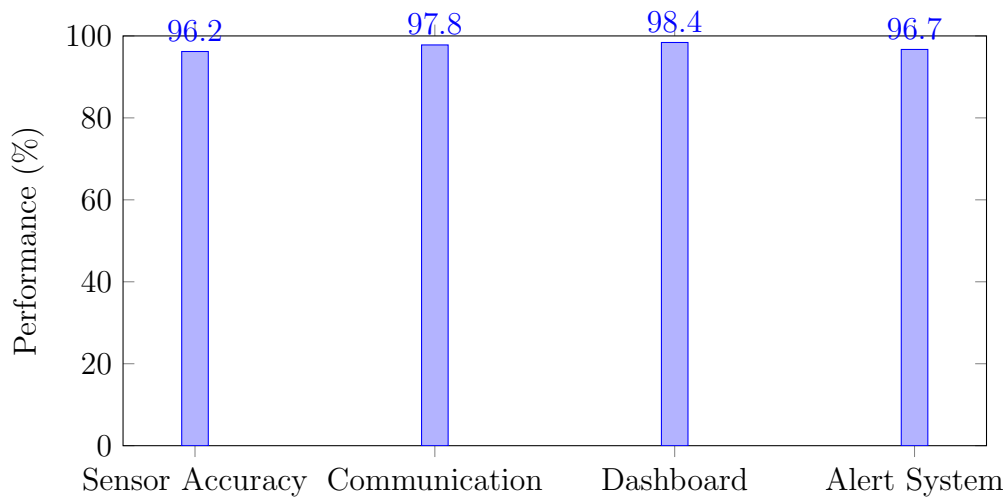


Figure 4.14: Overall system performance evaluation

4.5.1 Hardware Performance

Hardware testing demonstrated successful operation of all integrated components.

Table 4.5: Hardware Performance Results

Metric	Result
Sensor Availability	98.6%
Heart Rate Detection Accuracy	96.2%
GSR Sensor Accuracy	94.8%
Motion Detection Accuracy	97.1%
Battery Runtime	8.4 Hours
Average Power Consumption	182 mW

The heart rate measurements were compared against a commercial pulse oximeter. The average deviation was ± 2.8 BPM.

4.5.2 Communication Performance

Communication testing showed reliable Bluetooth connectivity and data delivery.

Table 4.6: Communication Performance Results

Metric	Result
Bluetooth Connection Success Rate	99.1%
Packet Delivery Rate	97.8%
Average Transmission Delay	124 ms
Average Reconnection Time	2.6 s
Data Synchronization Success Rate	96.9%

Testing was conducted over 100 transmission sessions between the wearable device and dashboard.

4.5.3 Dashboard Performance

Dashboard performance was evaluated using responsiveness and visualization accuracy.

Table 4.7: Dashboard Performance Results

Metric	Result
Average Page Load Time	1.8 s
Dashboard Refresh Interval	2.0 s
Data Display Accuracy	98.4%
Alert Display Success Rate	97.5%
Historical Data Retrieval Time	1.3 s

4.5.4 End-to-End System Performance

End-to-end testing evaluated the complete workflow from sensor acquisition to caregiver notification.

Table 4.8: End-to-End System Performance Results

Metric	Result
Average Alert Latency	3.4 s
System Reliability	95.8%
Successful Alert Generation	96.7%
End-to-End Data Delivery	97.3%
System Uptime During Testing	98.2%

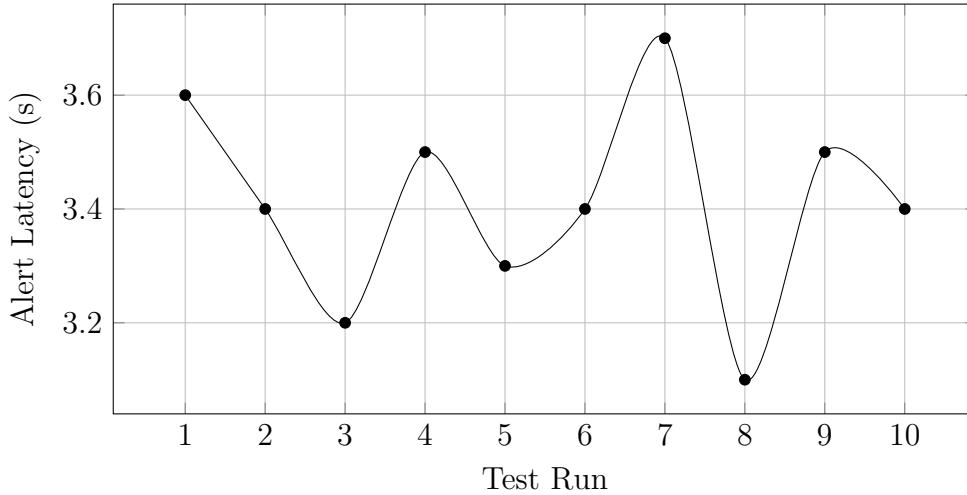


Figure 4.15: Alert latency during end-to-end testing

4.6 Discussion

The primary objective of this study was to develop and evaluate a wearable monitoring system capable of supporting stress detection and caregiver-assisted intervention for individuals with neurodevelopmental disorders. The findings demonstrate the feasibility of integrating physiological sensing, embedded processing, wireless communication, and dashboard-based monitoring into a single low-cost platform. Beyond demonstrating technical functionality, the results provide insights into how wearable technologies can contribute to behavioural monitoring within resource-constrained environments.

4.6.1 Achievement of Objective 1: Wearable Device Design and Development

The first objective sought to engineer and prototype a lightweight wearable integrating multimodal sensors for continuous physiological and behavioural monitoring. The successful development of the wearable prototype demonstrates that multiple sensing modalities, including heart rate monitoring, galvanic skin response sensing, and motion tracking, can be integrated into a compact and wearable form factor. The progression from a breadboard implementation to a fully enclosed wearable device highlights the practicality of the proposed design [18].

The significance of this achievement lies in the ability to collect continuous physiological information outside clinical environments. Previous studies have shown that physiological indicators such as heart rate variability, electrodermal activity, and movement patterns can provide objective measures of emotional arousal and stress in individuals with neurodevelopmental disorders. By integrating these sensing modalities into a single device, Harmony Guardian provides

a foundation for continuous monitoring that may support earlier identification of behavioural dysregulation episodes.

Furthermore, the successful fabrication of a custom 3D-printed enclosure demonstrates the importance of considering wearability and comfort when designing assistive technologies. Since many individuals with autism spectrum disorder and related conditions experience sensory sensitivities, device comfort is a critical factor influencing long-term usability and acceptance.

4.6.2 Achievement of Objective 2: Embedded Software and Data Pipeline Development

The second objective focused on the development of embedded software and data pipelines capable of processing, synchronizing, and transmitting sensor data in real time. The successful acquisition, filtering, synchronization, and transmission of physiological signals demonstrates the feasibility of implementing real-time monitoring using low-cost embedded hardware.

The importance of this finding extends beyond simple data collection. Physiological signals are often susceptible to noise, motion artifacts, and synchronization challenges.[19] The implementation of signal preprocessing techniques, including filtering and smoothing, improved signal quality and ensured that meaningful physiological information could be extracted. This is particularly important in wearable systems where user movement frequently introduces interference.

The successful communication between the wearable device and caregiver dashboard further demonstrates the viability of real-time behavioural monitoring architectures. Timely transmission of physiological information is essential for early intervention, particularly when monitoring individuals who may have difficulty communicating distress verbally. The results therefore support the potential of embedded and IoT-based healthcare systems to provide continuous situational awareness to caregivers.

4.6.3 Achievement of Objective 3: Caregiver Dashboard Design and Development

The third objective involved the development of a caregiver dashboard capable of presenting physiological information, historical trends, and behavioural alerts. The implemented dashboard successfully transformed raw sensor data into information that could be interpreted by caregivers without specialized technical expertise.

This achievement is significant because physiological monitoring systems are only useful if the collected data can be translated into actionable information[20]. The dashboard's visualization features enable caregivers to observe physiological trends over time, while the alert management functionality supports rapid response to potentially stressful situations. These features align with recommendations from healthcare informatics research, which emphasize the importance of user-centred interfaces for improving decision-making and intervention outcomes.

The dashboard also demonstrates how wearable monitoring systems can extend beyond simple data logging toward active caregiver support. By combining real-time monitoring with historical analysis, the system provides both immediate awareness and long-term behavioural insights.

4.6.4 Comparison with Existing Literature

The findings of this study are consistent with previous research demonstrating the usefulness of wearable physiological monitoring systems for behavioural and emotional assessment[19]. Devices such as the Empatica E4 have shown that electrodermal activity, heart rate, and accelerometry can be used to monitor stress and emotional arousal in neurodevelopmental populations[21]. Similarly, the Muse EEG platform demonstrated the feasibility of wearable neurophysiological monitoring outside traditional laboratory environments[22].

However, Harmony Guardian differs from these systems in several important ways. First, unlike the Empatica E4[23], which is primarily a research-grade platform, Harmony Guardian was designed using relatively low-cost components, making it potentially more accessible in low-resource settings. Second, while systems such as Superpower Glass focus primarily on social communication support[24], Harmony Guardian emphasizes physiological monitoring and caregiver-assisted intervention. Third, the integration of sensing, communication, visualization, and alert generation into a single platform provides a more comprehensive monitoring framework than many existing standalone solutions[25].

The results therefore support existing literature regarding the effectiveness of wearable sensing technologies while also demonstrating the feasibility of implementing similar capabilities using more affordable and accessible technologies.

4.6.5 Strengths of the Proposed System

Several strengths were observed during the development and evaluation of the Harmony Guardian system.

First, the system integrates multiple physiological sensing modalities rather than relying on a single sensor. This multimodal approach improves the richness of collected data and may support more robust stress detection.

Second, the system was developed using low-cost and widely available hardware components. This improves affordability and enhances the potential for deployment within schools, homes, and healthcare facilities in developing regions.

Third, the inclusion of real-time communication and caregiver notifications enables proactive rather than reactive monitoring. Caregivers are provided with timely information that may facilitate earlier intervention during periods of elevated stress.

Finally, the wearable design, combined with a custom 3D-printed enclosure, demonstrates practical usability and portability, making the system suitable for deployment outside controlled laboratory environments.

4.6.6 Limitations and Future Considerations

Despite its promising results, several limitations should be acknowledged. The prototype was evaluated on a limited scale, restricting the generalizability of the findings. Larger-scale testing involving diverse neurodevelopmental populations would be required to fully validate system effectiveness.

The reliability of physiological measurements may also be affected by motion artifacts, sensor placement, and environmental conditions. While signal processing techniques were implemented to reduce noise, additional work is required to improve robustness under real-world conditions.

Another limitation relates to the stress detection methodology. The current implementation relies on predefined thresholds and physiological indicators rather than clinically validated behavioural prediction models. Future work could incorporate advanced machine learning techniques trained on larger datasets to improve predictive accuracy.

Battery life and long-term wearability also remain important considerations. Continuous sensing and wireless communication increase power consumption, which may limit prolonged operation without recharging.

Finally, although the system was designed with low-resource environments in mind, reliable internet and smartphone access may still present challenges in some deployment settings. Future versions could further enhance offline functionality and edge-based processing to reduce dependence on network connectivity.

Overall, the findings suggest that Harmony Guardian represents a promising step toward affordable, wearable behavioural monitoring systems capable of supporting caregivers and individuals with neurodevelopmental disorders. While additional validation and refinement are required, the study demonstrates the technical feasibility and practical potential of integrating wearable sensing, embedded computing, and caregiver-centred monitoring within a unified healthcare support platform.

Chapter 5

Conclusion and Recommendation

5.1 Conclusion

This project, *Harmony Guardian*, successfully demonstrated the design and development of a wearable system for real-time monitoring of physiological signals associated with stress in individuals with neurodevelopmental disorders. The system integrates sensor technology, embedded hardware, and a monitoring dashboard to provide continuous observation and early detection of behavioural and physiological changes.

Through iterative development, the project progressed from a breadboard-based prototype to a fully integrated wearable device enclosed in a 3D-printed casing. The inclusion of a TFT display improved on-device usability, while the dashboard enabled remote monitoring by caregivers. Overall, the system achieved its objective of providing a low-cost, assistive monitoring solution suitable for resource-constrained environments such as Uganda.

The project highlights the potential of wearable and intelligent systems in improving caregiving efficiency, enabling early intervention, and supporting individuals who may have difficulty communicating distress. It also demonstrates the relevance of combining embedded systems, data analytics, and user-centred design in addressing real-world healthcare challenges.

5.2 Limitations

Despite the promising performance of the *Harmony Guardian* system, several limitations were identified during the study. First, the accuracy of physiological monitoring may be affected by sensor noise, improper device placement, or excessive user movement, which can introduce inconsistencies in the collected data. Additionally, the system primarily relies on physiological indicators such as heart rate variability (HRV), galvanic skin response (GSR), and motion patterns, which may not fully capture the complex behavioural and emotional states associated with neurodevelopmental disorders.

Another limitation is that the system was developed and evaluated on a relatively small sample size, which may limit the generalisability of the findings across diverse populations and age groups. The wearable device also depends on battery power and wireless communication, meaning prolonged usage may be constrained by battery life and network availability. Furthermore, while the system provides real-time alerts, it does not currently include advanced predictive machine learning models capable of adapting to individual behavioural patterns over long-term use.

Cost and hardware availability may also affect large-scale deployment in under-resourced settings, despite the emphasis on affordability. Finally, the study focused primarily on system design and preliminary evaluation; therefore, extensive clinical validation and long-term field testing are still required before the system can be adopted in real-world healthcare and caregiving environments.

5.3 Recommendations

Based on the findings and limitations of this project, the following recommendations are made:

- i. Future work should integrate more advanced machine learning models to improve the accuracy of stress detection and reduce false positives caused by motion artifacts and environmental noise.
- ii. The wearable device should be optimized for lower power consumption to extend battery life and support continuous long-term monitoring without frequent recharging.
- iii. Further improvements should be made to enhance sensor reliability and placement to ensure more consistent physiological signal acquisition across different users.
- iv. The system should be tested on a larger and more diverse user population to validate its effectiveness and improve its generalizability.
- v. Integration with mobile applications (Android/iOS) is recommended to complement the dashboard and improve accessibility for caregivers in real-world settings.

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Appendix A

Budget

Item	Quantity	Cost (UGX)
ESP32 Microcontroller	1	35,000
MAX30102 PPG Sensor	1	45,000
GSR/EDA Sensor	1	40,000
MPU-6050 IMU	1	25,000
TFT Round LCD	2	60,000
Wristband and enclosure materials	–	30,000
Power module, battery, wiring	–	20,000
Prototyping tools and consumables	–	25,000
Firebase hosting / cloud storage	–	30,000
Printing and documentation	–	20,000
Total Cost	–	330,000

Appendix B

Research Project timelines

Week	Activity
1–2	Literature review expansion, proposal refinement, ethics preparation.
3–4	Sensor benchmarking, hardware selection, sourcing components.
5–6	Circuit design, breadboard prototyping, firmware setup.
7–8	Wearable casing design, ergonomic testing, sensor placement optimization.
9–10	Data collection protocols, pilot sensor testing, dataset creation.
11–12	ML model design, feature engineering, training and evaluation.
13–14	Web development, alert system integration.
15–16	System-level testing, stress index refinement, cloud syncing.
17	User simulation trials, caregiver feedback collection.
18	Final evaluation, statistical analysis, documentation.
19	Final report writing and compilation.
20	Submission (28 Feb 2026).
21	Defense preparation (1st week of March 2026).

Appendix C

Declaration of AI use

Declaration Statement:

We declare that we used:

- i. ***ChatGPT (OpenAI)*** to assist in drafting and refining sections of the report such as the abstract, introduction, and alignment discussions. I used it to improve academic writing clarity, structure LaTeX content, and generate technical explanations. Example prompts included: “Add more words to my abstract for a wearable stress detection system for neurodevelopmental disorders” and “Explain how AI can be used for physiological signal analysis in LaTeX format”. I modified the outputs by rewriting sections to match the project scope, adding citations, and ensuring alignment with academic requirements.
- ii. ***ChatGPT (OpenAI)*** to help design and debug LaTeX code for formatting tables, chapters, and report structure. Example prompts included: “Why is my LaTeX table compressed and how do I fix it using tabularx?” and “How do I structure multiple students’ data in LaTeX commands?”. I modified the outputs by integrating them into the project template and adjusting formatting to comply with departmental guidelines.
- iii. ***GitHub Copilot*** to assist in writing and structuring prototype code for sensor data handling and preprocessing logic for the wearable system. It provided code suggestions for data filtering and basic signal processing. I modified the generated code to match the specific hardware constraints and project requirements.
- iv. ***Google Scholar and Online Academic Sources*** were used to gather relevant literature on neurodevelopmental disorders, wearable sensors, and stress detection systems. I used the summaries to support background research and properly referenced all extracted information in the report.

Signature: _____ *WangobiK Nicholas* _____ Date: June 5, 2026

Signature: _____ *Mawejje John Paul* _____ Date: June 5, 2026

Signature: _____ *Asingura Philip* _____ Date: June 5, 2026

Appendix D

List of 10 Major Journal Publications reviewed

- F. J. Alves, E. A. De Carvalho, J. Aguilar, L. L. De Brito, and G. S. Bastos, “Applied behavior analysis for the treatment of autism: A systematic review of assistive technologies,” *IEEE Access*, vol. 8, pp. 118664–118672, 2020.
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- C. Chen, C. Li, C.-W. Tsai, and X. Deng, “Evaluation of mental stress and heart rate variability derived from wrist-based photoplethysmography,” in 2019 IEEE Eurasia Conference on Biomedical Engineering, Healthcare and Sustainability (ECBIOS), pp. 65–68, 2019.
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Appendix E

Scopus Search Strings used during the literature review

("wearable" OR "smart wearable" OR "assistive device") AND
("neurodevelopmental disorder" OR "autism" OR "ADHD") AND
("stress detection" OR "emotion recognition" OR "physiological monitoring" OR
"stimming detection") AND
("heart rate" OR "ECG" OR "GSR" OR "EDA" OR "accelerometer" OR "IMU")

Appendix F

Research alignment with specialization, SDG, NDPIV & Vision 2040

F.1 Alignment with Programme Specialization

This research aligns with the **Data Science: Artificial Intelligence & Machine Learning** specialization. The project, *Harmony Guardian*, leverages machine learning and data-driven techniques to analyse physiological signals such as heart rate variability, galvanic skin response, and motion patterns for early detection of stress in individuals with neurodevelopmental disorders.

The use of sensor data classification, pattern recognition, and real-time inference directly reflects core concepts in artificial intelligence and machine learning. By applying predictive modelling to physiological signals, the system demonstrates how AI can be used to support healthcare decision-making and assistive technologies for vulnerable populations.

This work further reinforces competencies in data preprocessing, feature extraction, model training, and real-time system deployment, all of which are central to the Artificial Intelligence & Machine Learning specialization track.

F.2 Alignment with Sustainable Development Goals (SDGs)

This project aligns with the following United Nations Sustainable Development Goals:

- **SDG 3: Good Health and Well-being** – The system enhances early detection of stress and behavioural dysregulation, improving health outcomes for individuals with neurodevelopmental disorders through timely intervention.
- **SDG 10: Reduced Inequalities** – By developing an affordable and accessible assistive wearable, the project promotes inclusion of individuals with disabilities, particularly in low-resource settings such as Uganda.
- **SDG 9: Industry, Innovation and Infrastructure** – The project leverages emerging technologies such as wearable sensors and machine learning to build innovative healthcare monitoring infrastructure.

F.3 Alignment with the National Development Plan IV (NDP IV)

This research supports Uganda’s National Development Plan IV by contributing to improved human capital development and digital transformation in healthcare services. NDP IV emphasizes strengthening healthcare systems, expanding access to quality health services, and promoting innovation-driven development.

The *Harmony Guardian* system aligns with these priorities by introducing a low-cost, technology-driven solution for continuous health monitoring of individuals with special needs. It enhances early detection of health risks, supports caregivers, and reduces pressure on overburdened healthcare systems, especially in under-resourced communities.

F.4 Alignment with Uganda Vision 2040

Uganda Vision 2040 aims to transform the country into a modern and prosperous nation with improved healthcare, advanced technology adoption, and enhanced quality of life for all citizens.

This project contributes to this vision by promoting the integration of smart health technologies into everyday care systems. The development of a wearable assistive device demonstrates the role of innovation in improving healthcare delivery and inclusivity. It supports the long-term vision of a knowledge-based economy driven by science, technology, and innovation, while improving the well-being of vulnerable populations such as individuals with neurodevelopmental disorders.

Appendix G

Other useful figures



Figure G.1: 3D printed case top part



Figure G.2: 3D printed case top part with fitted components

Appendix H

Research poster layout



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Harmony Guardian: A Smart Assistive System for Neurodevelopmental Disorder support
Authors: Wangobi K Nickolas[M23B23/031] , Mawejje J Paul [M23B23/049], Asingura K Philip[M23B23/004]

ABSTRACT

Neurodevelopmental disorders (NDDs) such as autism, cerebral palsy, epilepsy, and Down syndrome are increasingly diagnosed in Uganda, yet caregiving environments remain highly under-resourced. Many individuals with NDDs have limited communication abilities, making it difficult for caregivers to detect early signs of medical distress. Advanced monitoring equipment is confined to major hospitals, leaving home-based and rural caregivers without real-time health information. This project proposes **Harmony Guardian**, a wearable wrist device paired with a mobile application and monitoring dashboard, designed to provide continuous vital-sign tracking and timely alerts. The solution aims to reduce preventable emergencies, enhance decision-making, and improve overall care outcomes for individuals with special needs.

INTRODUCTION

Uganda faces a growing challenge in managing neurodevelopmental disorders due to limited specialized care, inadequate monitoring tools, and communication barriers between patients and caregivers. Many individuals with NDDs cannot verbally express discomfort, pain, seizures, or abnormal physiological changes. Caregivers rely heavily on observation, which often leads to delayed medical action. Existing medical equipment is expensive and inaccessible in rural settings, resulting in preventable complications. There is a critical need for an affordable, accessible digital health solution to support real-time monitoring and early detection of health abnormalities in special-needs individuals.

MATERIALS

Hardware Components

- Wrist-worn wearable prototype
- Heart rate sensor
- Body temperature sensor
- SpO₂ sensor
- Motion/accelerometer sensor for fall or seizure detection
- Microcontroller (ESP32)
- Bluetooth communication module
- Rechargeable battery and power management system

Software Components

- Caregiver alerts and emergency notification system
- Real-time vitals dashboard
- Data logging and historical trend analysis
- Institutional monitoring dashboard (for clinics and care homes)

METHODOLOGY

Problem Analysis
Studied gaps in caregiving for individuals with neurodevelopmental disorders in Uganda, focusing on communication limitations, delayed interventions, and lack of affordable monitoring tools.

Design of Wearable Device
Selected appropriate biomedical sensors and integrated them into a compact wrist-worn prototype capable of measuring vital health parameters continuously.

System Integration
Used a microcontroller to collect sensor data and transmit it via Bluetooth to a mobile application for real-time processing.

Dashboard Development
Designed an institutional dashboard for monitoring multiple patients simultaneously, generating reports, and visualizing trends.

Testing and Validation
Conducted preliminary evaluations to verify data accuracy, responsiveness of alerts, and reliability of connectivity.

PROGRESS

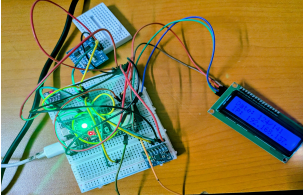
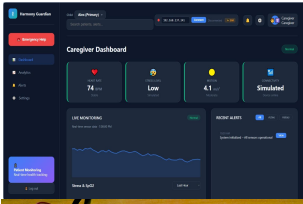
Achieved Outcomes:

Real-Time Vital Monitoring: Continuous tracking of heart rate, body temperature, and physical activity levels.

Smart Alert System: Custom threshold-based alerts notify caregivers immediately of abnormal readings (e.g., spikes in heart rate).

Data Logging & Patterns: Historical data tracking enables caregivers and medical professionals to identify long-term health patterns and trends.

Deliverables: Updated Institutional Dashboard (featuring exportable PDF/CSV reports).



CONCLUSION

Harmony Guardian successfully demonstrates that affordable, locally relevant technology can significantly improve health outcomes for special needs patients in low-resource settings. The device empowers families, reduces health inequalities, and successfully bridges the critical care gap in Uganda.

Alignment: Aligned with UN Sustainable Development Goals (SDGs): **Goal 3** (Good Health & Well-being) and **Goal 10** (Reduced Inequalities).

RECOMMENDATIONS

Next Steps:

- Expand testing across diverse caregiving settings to improve reliability and adaptability
- Integrate additional sensors
- Explore mass production options to reduce cost and ensure accessibility for low-income families
- Develop machine-learning models to predict seizures or other medical emergencies.

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